FUNDAMENTALS OF LIGHT and LIGHTING

LARGE LAMP DEPARTMENT

GENERAL ELECTRIC

FUNDAMENTALS OF LIGHT AND LIGHTING

By Walter Sturrock and K. A. Staley

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FUNDAMENTALS OF LIGHT AND LIGHTING

PART I — INTRODUCTION

Adequate light properly distributed and normal vision are the essential elements for quick, accurate, and easy seeing. Poor lighting wastes human resources. Improved illumination practice has many benefits such as increased safety and reduced fatigue in industrial plants, and greater ease of seeing in offices and schools. In stores, it adds attraction value to merchandise, quickens appraisal by the shopper, and creates atmosphere in architectural and decorative harmony.

For the successful application of lamps and lighting equipment, it is essential to have a basic understanding of the nature of light and how we see, the physics of light and its measurement, methods of control, characteristics of materials used in lighting equipment, and the principles of illumination design. This bulletin outlines many fundamentals on these subjects.

By extension, the art and science of illumination includes the application of ultraviolet and infrared radiation. The principles of measurement, methods of control, and many design fundamentals in these fields closely parallel those long established in lighting practice.

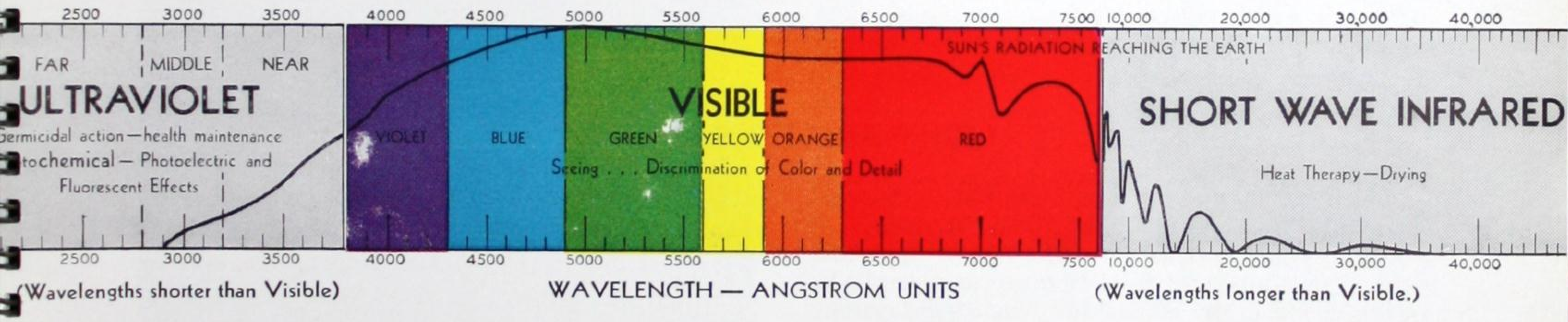


Fig. 1. The art and science of illuminating engineering include the application of ultraviolet, visible, and infrared energy.

LIGHT AND RADIANT ENERGY

For the purposes of illuminating engineering, *light is defined as visually evaluated radiant energy.* It is generally accepted that light sources radiate visible energy in waves which are found in an extremely narrow band in the electromagnetic spectrum. This visible energy band extends from 3800 to 7600 Angstroms (254,000,000 Angstroms = 1 inch). When these energy waves enter the eye, vision takes place. As may be seen from the spectrum chart, Fig. 1, the shortest visible waves produce violet light, the longest produce red light. The mixture of all colors produces white light.

The band of energy just longer than the red light-rays is termed "infrared," the prefix, "infra" is the Latin word meaning "below." The relationship of these adjoining energy bands, heat or infrared energy and light or visible energy, can be visualized from the familiar example of turning on the heating element of an electric range. Placing one's hand close to the element, a sensation of heat can be felt almost immediately. As the molecules of the element increase the rate of transformation of electrical energy into heat, part of the waves become shorter and finally some of them emerge from the infrared region and enter the visible region, the range to which our eyes are tuned. The element glows a dull red at first, then brightens to a cherry red.

If the control mechanism did not limit the current and the element transformed increased amounts of electrical energy, it would ultimately become white hot, which would indicate the presence of all of the colors of light: violet, blue, green, yellow, orange, and red.

If the heating element material were of tungsten, as in a conventional filament lamp, a small part of the energy would be transformed into waves shorter than those in the visual band, into the adjoining "ultraviolet" region. The prefix "ultra" is the Latin word meaning "beyond." In tungsten-filament lamps ultraviolet energy is generated in infinitesmal amounts, but in generous quantities in a highly efficient manner in gaseous-discharge lamps. The latter are generally tubular in shape, contain mercury vapor, and are arc-discharge lamps.

Their ultraviolet energy is very useful; these invisible rays are supplied by sunlamps which produce suntan. The lamps are used in hospitals, solaria, and homes. The still shorter wave ultraviolet energy from germicidal lamps is used for destroying bacteria in air, liquids, or on surfaces.

Fig. 2. Light is invisible; the beam of a flashlight is visible only because dust particles in the air reflect light energy toward the eye.

Light energy is also invisible. This paradox may be demonstrated by pointing a focussing-type flashlight at the sky on a dark night. The beam may be sufficient to act as a pointer to indicate a star position but upon close examination what are actually seen in it are the dust particles (motes) or vapor particles in the air which reflect minute quantities of light toward the eye. In a photometric laboratory with its characteristic black walls, a beam of light is virtually invisible, especially when viewed at right angles to the beam. We see the *effect* of the light energy projected to our eyes or reflected from some surface or object, but not the light itself. Light is ultimately dissipated by transformation into heat in the object and in the surrounding media.

LIGHT AND HOW WE SEE

Much as an electric lamp transforms electrical energy into heat and light, the visual "apparatus" of a human being acts as a transformer of light into sight. Light projected from a source or reflected by an object enters the cornea and lens of the eyeball. The energy is transmitted to the retina of the eye (Fig. 3) whose rods and cones are activated.

The stimuli are transferred by nerve cells to the optic nerve, and then to the brain. Man is a binocular animal, and the impressions from his two eyes are translated into sight . . . a rapid, compound analysis of the shape, form, color, size, position, and motion of the things he sees.

As may be seen from Fig. 3, the retina of the eye forms the curved back wall of the eyeball and serves as the film of this "living camera." Imbedded in its structure are two kinds of receptors, called rods and cones, which are named for their respective shapes. The estimated 130 million rods in the human retina function principally at low levels of illumination (less than moonlight), in so-called night vision (scotopic).

The cones number approximately 7 million and are responsible for both color vision and the recognition of fine detail at levels above moonlight (photopic vision). The cones are the only receptors in the fovea which is the small area of the retina with which we focus upon objects or surfaces. This area at 14 inches is so small that the eye must change position to focus on the two dots in a colon (:).

When the eye is subjected to very low illumination, vision is crude and lacking in detail. Individuals vary in their scotopic vision; poor night vision or night blindness is partially attributed to the lack of Vitamin A. Dark adaptation is gradual and is not substantially complete for half an hour or more.

Since the rods are relatively insensitive to red light, a dimly-lighted red area is normally detected by an observer only when his line of sight passes within a degree or two of a line normal to the surface.

On the other hand, rods are particularly sensitive to blue light. A dimly lighted blue area can be readily detected by peripheral vision, by not looking directly at it, and the effect is noticeable over a wide angle from the direct line of sight. A faint, bluish star, for example, can be more readily detected at night by looking "out of the corner of the eye." For this reason, during war-time blackouts, reddish light served best to facilitate ground and shipboard activities, and was at the same time least likely to be detected from the air.

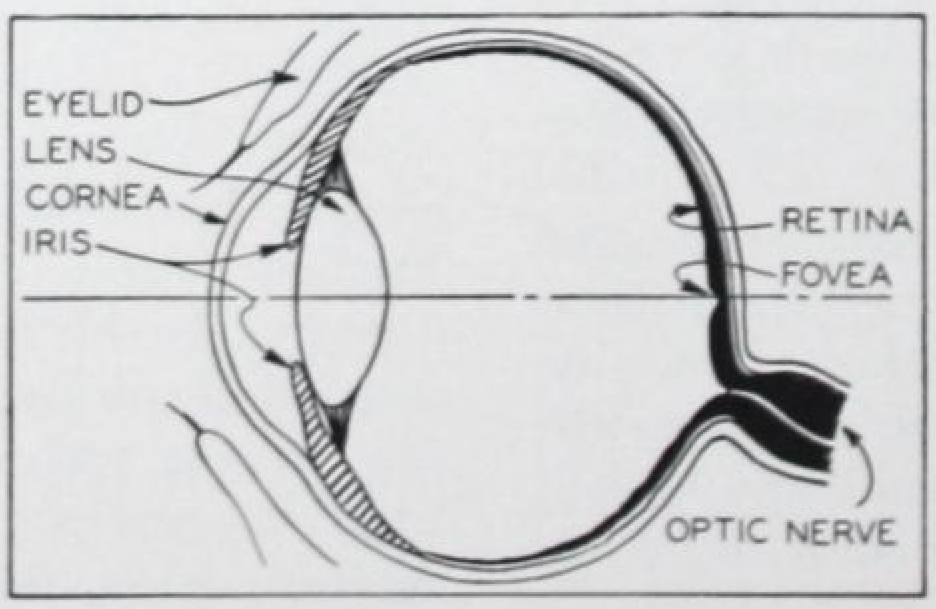


Fig. 3. The human eye.

PART II
—PHYSICS OF LIGHT

THE MEASUREMENT OF LIGHT—PHOTOMETRY

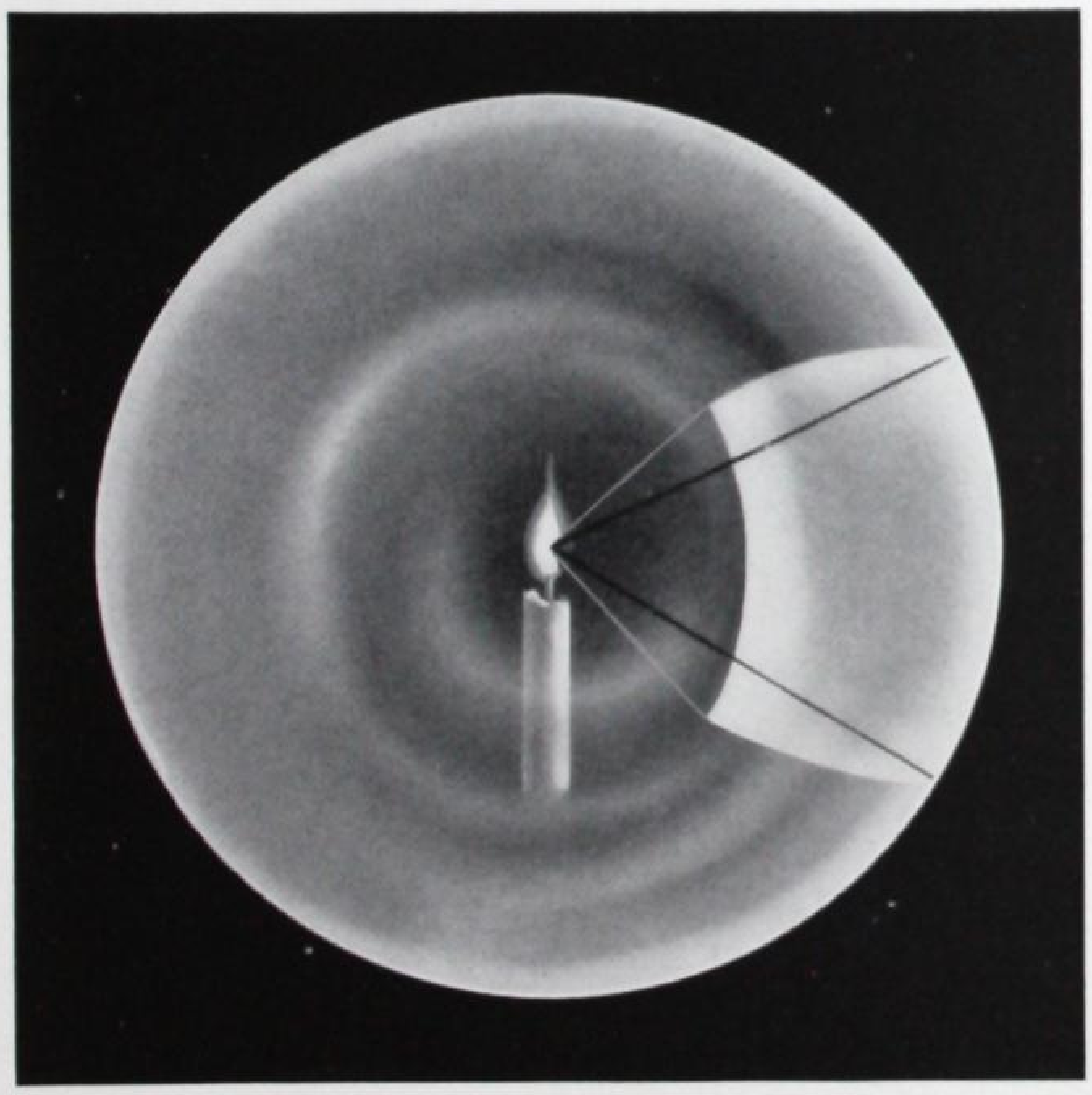
Photometry is the science of measuring light. The illuminating engineer and designer employ photometric data constantly in their work. In all fields of application of light and lighting, they predicate their choice of equipment, lamps, wall finishes, colors of light and backgrounds, and other factors affecting the luminous and environmental pattern to be secured, in great part from data supplied originally by a photometric laboratory. Today, extensive tables and charts of photometric data are used widely, constituting the basis for many details of design.

Although the lighting designer may not be called upon to do the detailed work of making measurements or plotting data in the form of photometric curves and analyzing them, an understanding of the terms used and their derivation form valuable background knowledge.

Most of the terms used in measuring light are based on the relationships existing when a one-candlepower source is assumed to be at the center of a hollow sphere having a radius of one foot (Fig. 4). The source is presumed to give light equally in all directions and to be of such relatively small dimensions that it is termed a "point source." The surface area of a sphere is $4\pi \times r^2$ and since in the unit sphere, r equals one foot, the area is 12.57 square feet. The luminous flux radiated from the one-candlepower source to each square foot of the inside surface of the sphere is called a *lumen,* the Latin word for "light." Under these conditions, one candle or a one-candlepower source, therefore, is equivalent to 12.57 lumens.

In the early days of the lighting industry, the illuminating power of light sources was expressed in *horizontal candlepower* because the most natural direction from which the eye might observe a source was in a horizontal direction. The average horizontal candlepower was determined by rotating the lamp to be measured about its vertical axis while the readings were being taken, and the result was known as the mean or average horizontal candlepower of the source.

As lamps of greater output and devices for redirecting light into more useful directions were produced, the horizontal candlepower measurement had decreasing value as a means of rating light output, and the term, mean spherical candlepower, came into use. The *mean spherical candlepower* is an average of all the candlepowers in all directions about a source. For example, a source giving 10 candlepower in every direction would have a mean spherical candlepower of 10, or if a source gave off light in varying amounts in all directions such that their average were 10, its mean spherical candlepower would be 10. The term "candlepower" as applied to automotive and other miniature lamps actually indicates mean spherical candlepower and is abbreviated for convenience to "cp."



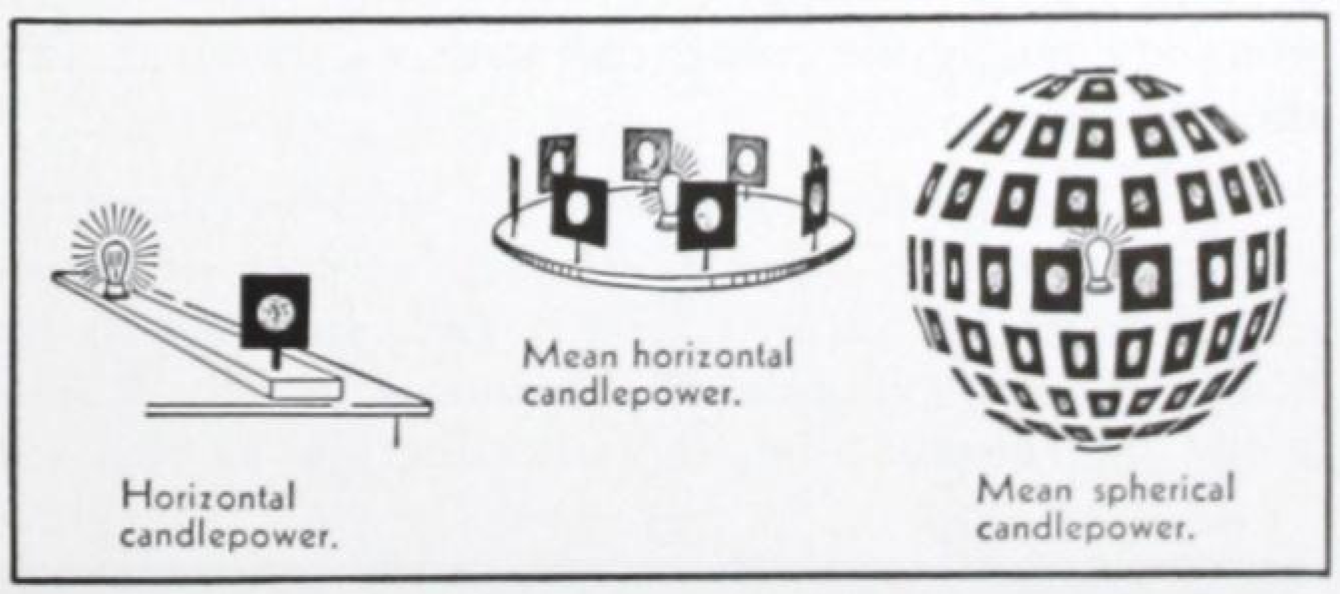


Fig. 4. Diagrammatic concepts of candlepower.

Illumination

Illumination on a surface or plane of work is measured in terms of the number of lumens per square foot of area. A "lumen per square foot" is called a *footcandle,* abbreviated "fc."

Since the unit sphere of Fig. 4 has just one lumen per square foot on its surface, the illumination is one footcandle and one can say that a surface one foot from a one-candlepower source is lighted to one footcandle.

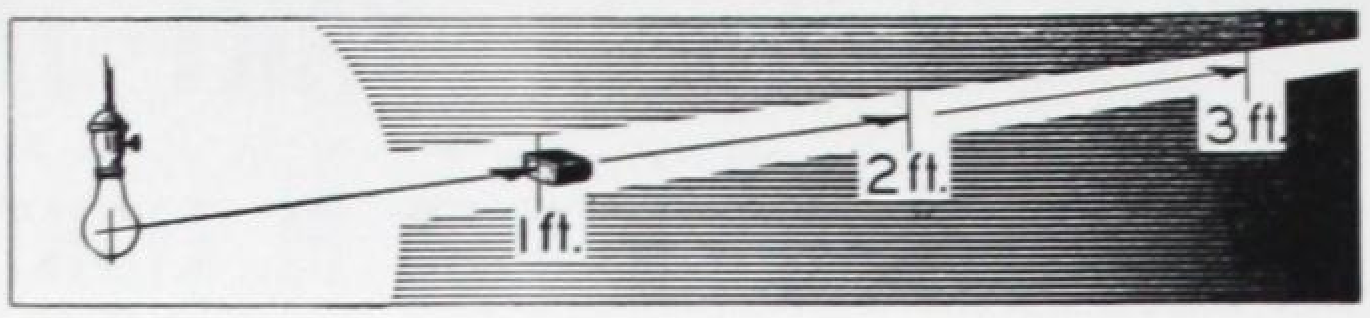


Fig. 5. The illumination at 2 ft. is ¼ of that at one foot. The illumination at 3 ft. is 1/9 as much. This effect is called the inverse square law.

The Inverse Square Law

A sphere with a radius of two feet has an area of $4\pi \times 2^2$ or about 50 square feet, which is four times as large as a sphere having a radius of one foot. Similarly, a sphere with a radius of three feet has an area of $4\pi \times 3^2$ or 112.5 square feet, which is *nine* times as large as the unit sphere. In other words, as the radius or distance from the center of the sphere is increased, the area lighted is increased in proportion to the squares of the distances. For a given point source of light, this means that the level of illumination decreases as the square of the distance from the source (Fig. 5). This is known as the *inverse square law* and is presented by the formula:

$$Fc = \frac{CP}{D^2} \qquad \text{where } CP = \text{candlepower}, \quad D = \text{distance}$$

One way to demonstrate this physical law is to measure the illumination from a filament lamp at distances of two, three, and four feet. The distances should be measured from the center of the source.

The inverse square law is used to calculate the amount of illumination from an individual light source on planes perpendicular to the beam. Strictly speaking, it applies only to illumination on a small surface from a **point** source. In practice, however, a point source is considered to be one whose dimensions are negligible compared with its distance from the surface.

The law applies to distances 5 or more times the maximum source dimension. For shorter distances, the illumination varies approximately inversely *as* the distance. For example, if the source of Fig. 5 were a 48″ fluorescent tube, the illumination at two feet would be approximately ½ that at one foot; at three feet, it would be approximately ⅓. See also Table A, page 98.

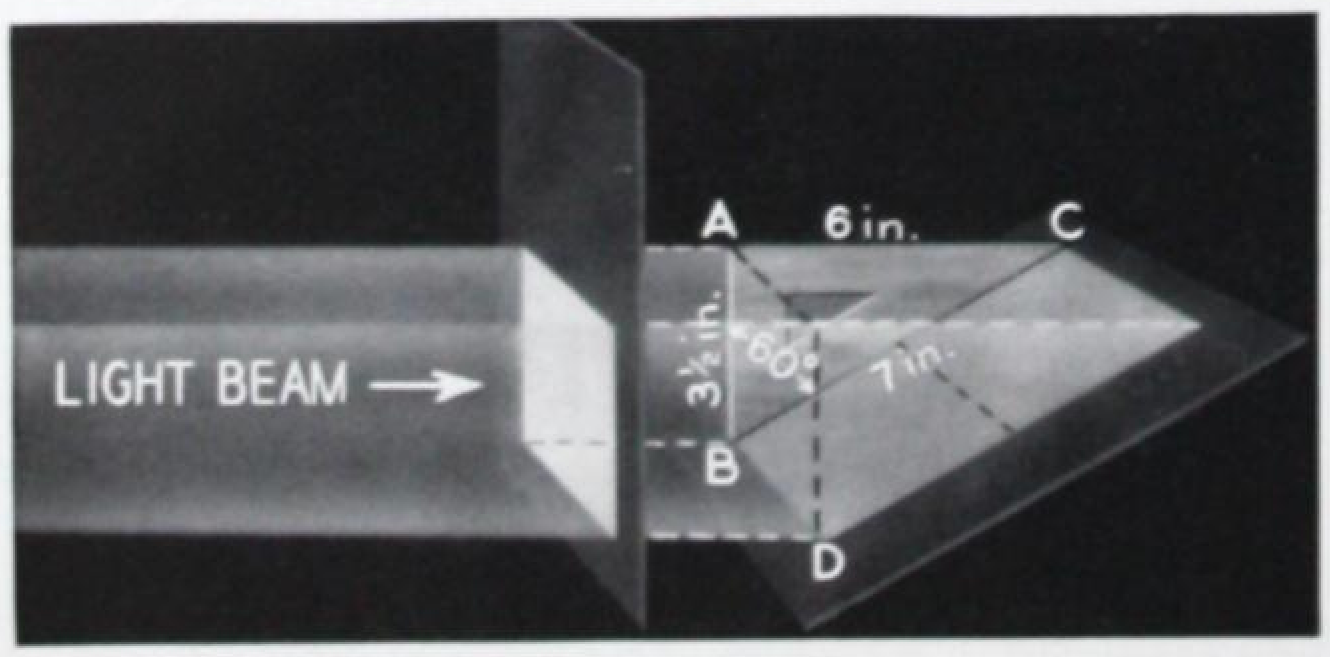


Fig. 6. The ratio of the base of a right-angle triangle to its hypotenuse is the cosine of the angle ABC. For 60 degrees, the ratio is ½ or 0.5. The average light on a surface tilted at this angle is ½ of that on the surface normal to the beam of light, the tilted surface is twice as large.

Cosine Law of Incident Light

When a surface is not perpendicular to a beam of light, the illumination on it is less because the light is spread over an area of greater size. As shown in Fig. 6, the width of the tilted surface is the same as the width of the perpendicular surface, but its length and area are increased, depending upon the angle of tilt. (The angle of tilt is ABC, 60 degrees. See Fig. 6.)

The perpendicular area is square and is equal to AB x BD. The tilted area is rectangular and is equal to BD x BC. The dimension BC is twice as long as AB, hence, the tilted area is twice as large and the average illumination on it is therefore half as much.

The ratio of the two areas may be more simply expressed as $\frac{AB}{BC}$. This ratio of the parts of the triangle is termed the **cosine** of the angle ABC.

The meaning of the term **cosine** is illustrated by the draftsman's 30°-60° triangle in Fig. 6. In this "6-inch" triangle, the cosine of the angle is the ratio of AB to BC (3½ inches to 7 inches) or ½ or .500.

The relation known as Lambert's cosine law is that the illumination on a tilted plane is equal to the illumination on a normal (perpendicular) plane times the cosine of the angle of incidence.

The expression may be written as follows:

$$Fc = \frac{CP \times \cos a}{D^2}$$

and it is quickly evident how the inverse square law is included.

Table of Cosines

Cosines of angles which are useful in photometric calculations are given below:

Angle in Degrees	Cosine	Angle in Degrees	Cosine
0°	1.0	45°	.707
5°	.996	50°	.643
10°	.985	55°	.574
15°	.966	60°	.500
20°	.940	65°	.423
25°	.906	70°	.342
30°	.866	75°	.259
35°	.819	80°	.174
40°	.766	85°	.087
		90°	0

Fig. 7. Cosines of angles.

THE CANDLEPOWER DISTRIBUTION CURVE

A candlepower distribution curve* is a graphic presentation of the distribution of light intensity of a lamp or luminaire. Such presentations contribute valuable information to guide the engineer in determining the suitability of lighting equipments for application in various fields. As a background for using distribution curves it is first necessary to see how they are obtained.

The candlepower in any direction from a filament lamp equals the footcandles produced on a plane at right angles to the light rays times the square of the distance in feet from the lamp to the point of measurement ($CP = Fc \times D^2$). For accurate measurements the distance should be at least five times the largest dimension of the source. (To simplify calculations 10 feet is often used in photometric laboratories.) If in this way the average cp. around the axis of a filament lamp is determined for any angle from the vertical, say 25°, the average value becomes one point which can be plotted to a convenient scale on polar-coordinate paper. Taking several measurements around the axis at the 25° angle from the vertical usually shows them all to be about the same. However, in laboratory photometry any slight differences that might be present because of filament structure or other variations are compensated by rotating the lamp so that one reading represents an average value.

To get sufficient data for a lamp or general lighting unit, 20 readings are usually taken at angles of 0°, 5°, 15°, 25°, 35°, 45°, etc., up to 180° (Fig. 8), and the candlepowers computed and plotted on polar-coordinate paper. A line connecting a series of such points forms the candlepower distribution curve. The value at 90° is the candlepower straight out from the unit while that at 0° is directly below. For concentrated light sources such as searchlights and spotlights, readings are often required one or two degrees apart, rather than at 10° intervals.

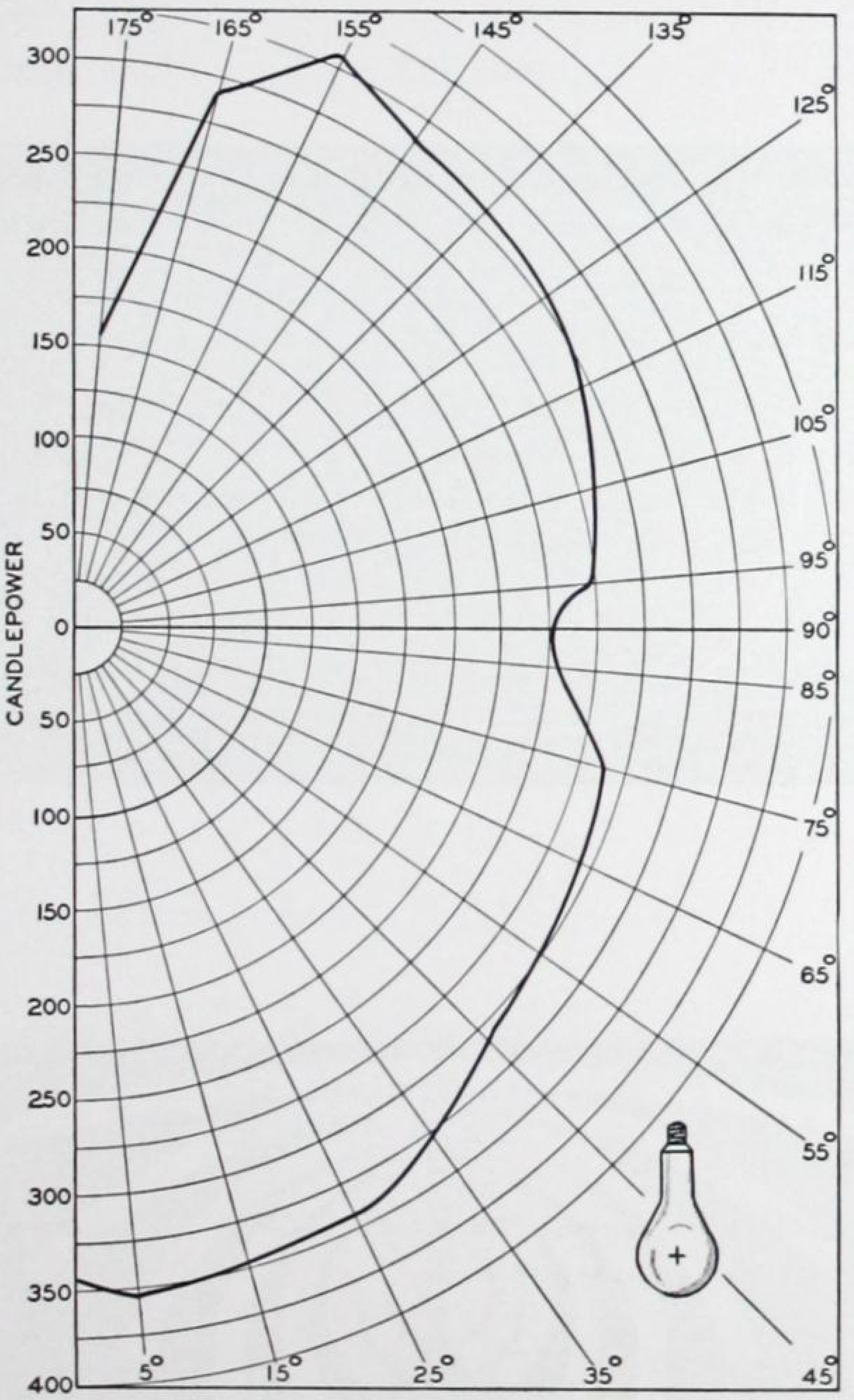


Fig. 8. Distribution curve of 200-watt filament lamp. For convenience the curves of symmetrical-type units show only the 0°—180° half. Actually the distribution of light includes 360°. The two halves are symmetrical.

COMPUTATION OF LUMENS FROM CANDLEPOWER VALUES

Angle	Candle-power	Zone	Zonal Constant†	Zonal Lumens
0	347			
5	352	0–10	.10	35
15	348	10–20	.28	97
25	342	20–30	.46	157
35	326	30–40	.63	205
45	307	40–50	.77	236
55	300	50–60	.90	270
65	288	60–70	.99	285
75	285	70–80	1.06	302
85	259	80–90	1.09	282
90	257			
95	271	90–100	1.09	295
105	278	100–110	1.06	295
115	290	110–120	.99	287
125	307	120–130	.90	276
135	308	130–140	.77	237
145	313	140–150	.63	197
155	329	150–160	.46	151
165	280	160–170	.28	78
175	153	170–180	.10	15
			Total Lumens	3700

† See page 8.

Fig. 9. Tabulation of Candlepower and Lumens in the various zones in the curve of Fig. 8.

* This would be an *erythemal distribution curve* when it indicated in E-vitons per steradian the ultraviolet energy which produces suntan from sunlamps. Or it would be a *germicidal distribution curve* in terms of microwatts per steradian as supplied by germicidal lamps. For infrared radiant energy from drying and heat lamps, the curve would be a *radiant energy distribution curve* in terms of watts per steradian.

Light Output

As previously defined, in the unit sphere one lumen of light falls on each square foot of the sphere's surface whether the area be square, round, irregular in shape, or a band around the sphere.

The next step is to divide the sphere into bands or zones; usually eighteen 10-degree zones are chosen from 0° beneath the unit to 180° directly above it. The number of lumens in each zone equals one candlepower times the area of the zone in square feet. Note that the 10° zones near the horizontal are much larger in area than the zones near the vertical axis.

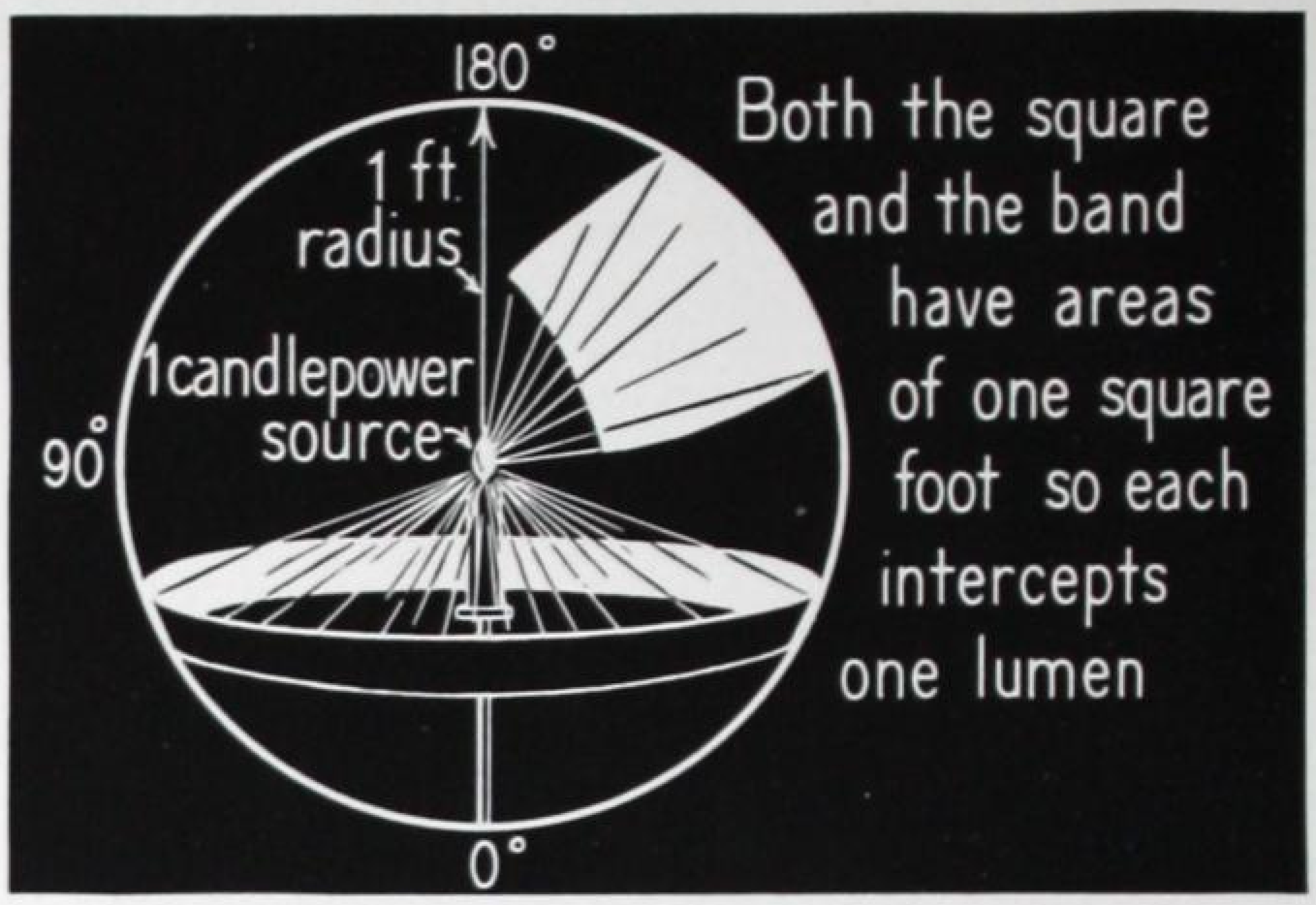
In Fig. 10 it is assumed that the sphere is covered with a material which can be peeled off in strips representing the individual zones. The area of the zones can also be determined mathematically; the actual values are shown in Table 1—Zonal Constants. It will be seen that their sum equals 12.56, which equals the number of square feet of surface in the unit sphere.

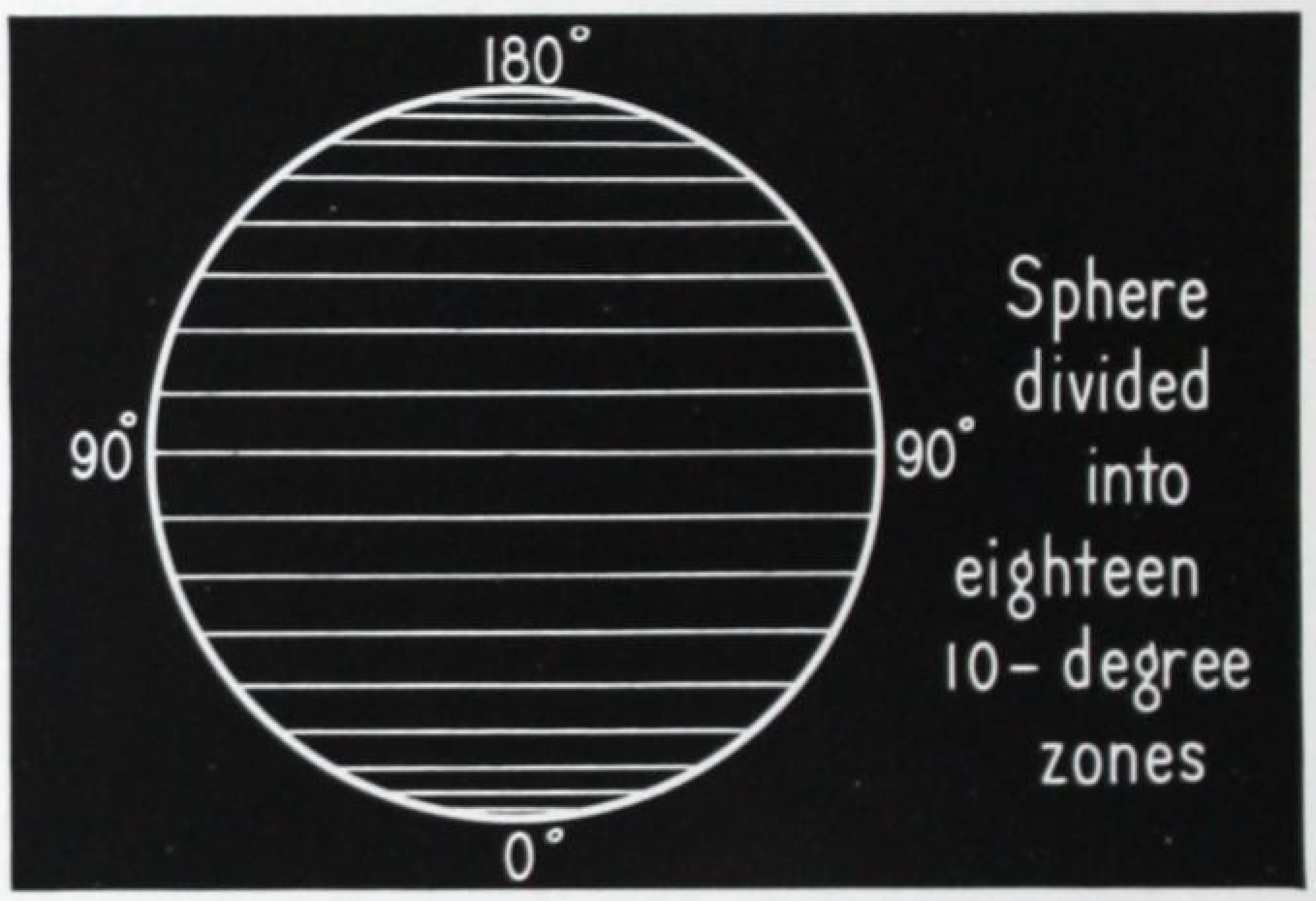
Since with a one-candlepower source in the unit sphere one lumen falls on each square foot, the lumens in each zone equal the area of the zone in square feet. Thus there is 0.10 lumen in the 0°—10° zone; it has an area of 0.10 sq. ft. In the 80°—90° zone, a ring of relatively large area, there are 1.09 lumens. If the one-candlepower source is replaced by a source of 10 candlepower, the lumens in each zone will equal the zonal constant times 10.

TABLE 1
ZONAL CONSTANTS

Zone	Zonal Constant	Zone	Zonal Constant
0°-10°	.10	170°-180°	.10
10°-20°	.28	160°-170°	.28
20°-30°	.46	150°-160°	.46
30°-40°	.63	140°-150°	.63
40°-50°	.77	130°-140°	.77
50°-60°	.90	120°-130°	.90
60°-70°	.99	110°-120°	.99
70°-80°	1.06	100°-110°	1.06
80°-90°	1.09	90°-100°	1.09

In the same way, the zonal constants can be applied to candlepower distribution curves with varying candlepower values. It is assumed that the candlepower in the center of the zone represents the average for that zone. Thus to get the lumens in the 0°—10° zone, the candlepower at 5° is multiplied by the zonal constant, 0.10. The lumens in the 80°—90° zone equals the 85° candlepower times 1.09, the constant for that zone. Or for example, as seen in Fig. 8, the 200-watt filament lamp gives 342 candlepower at 25° from the axis. Multiplying this by the zonal constant, 0.46, gives the value of 157 lumens for the 20°—30° zone.





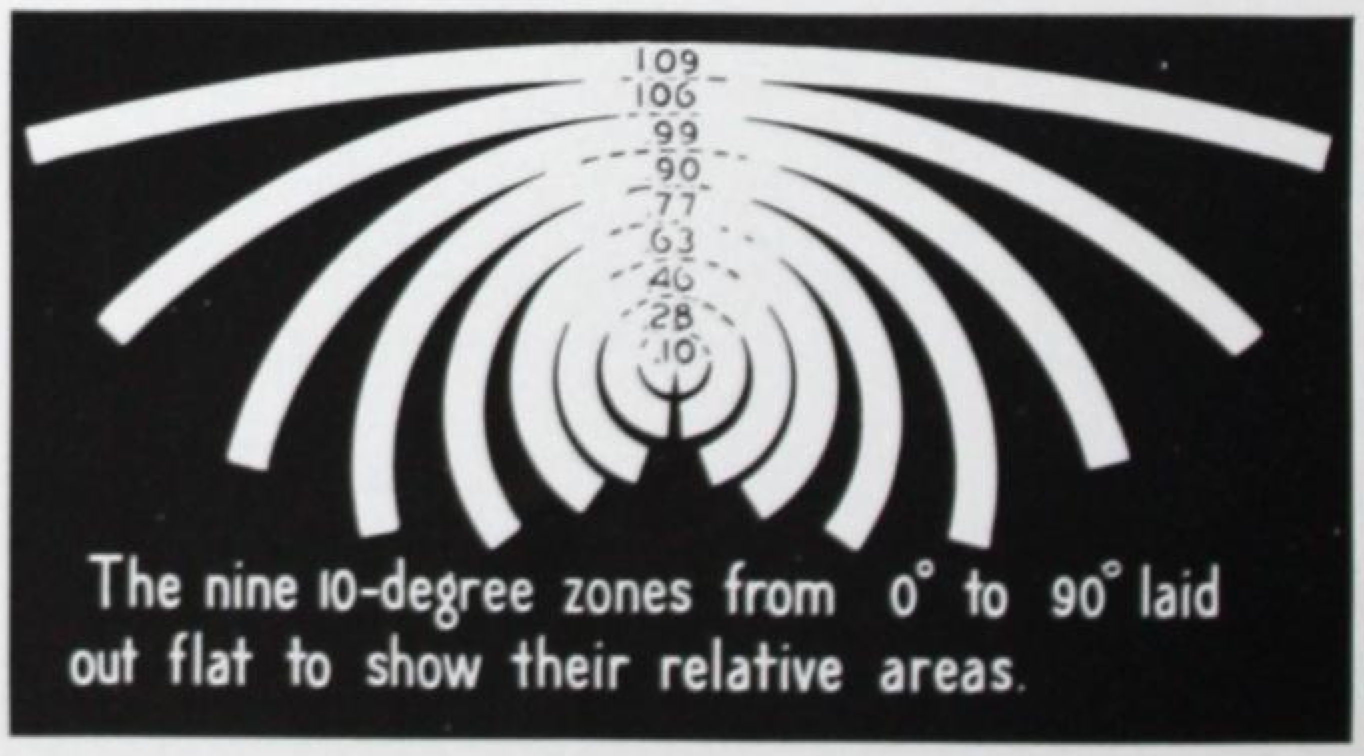
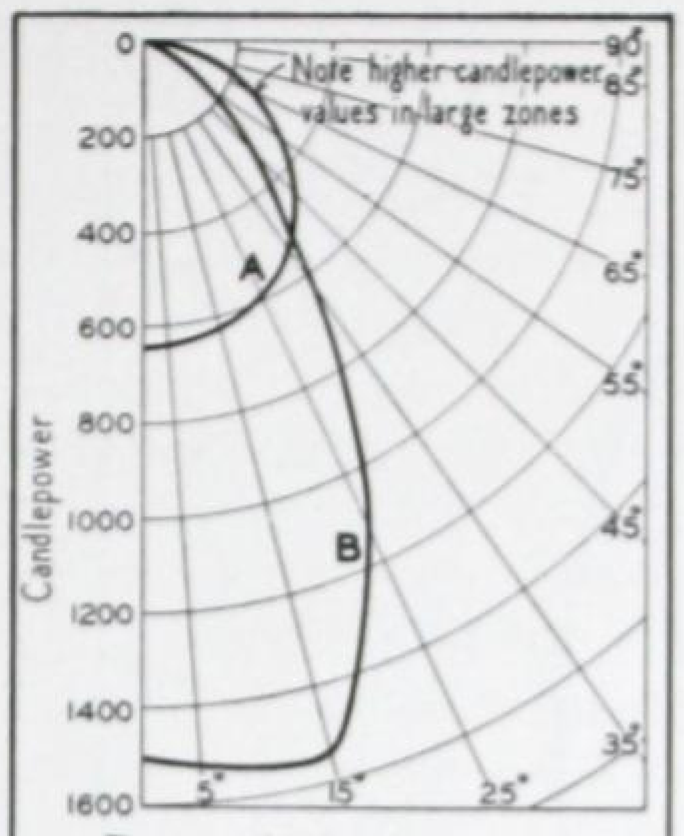


Fig. 10. Sphere divided into 10-degree zones.

The area of a candlepower distribution curve is not a criterion of a luminaire's output. The two curves (Fig. 11) are for direct luminaires having equal lumen output. It may be seen that curve B provides more light directly under the unit, but in curve A, the effect of the large zones near the horizontal is evident. An inexperienced person would assume that curve B represents many more lumens because, on the graph, it encloses a much larger area. But since the high candlepower values are in those small zones near the vertical, they account for relatively few lumens. The total lumen output is the sum of the lumens in each zone; it has no relation to the area enclosed by the curve. Another method for measuring the total lumen output of lamps and luminaires is discussed under the subject, "Photometric Laboratory Measurements," page 12.



The area of a distribution curve is not a criterion of a luminaire's output. These curves are for units which emit the same total lumens

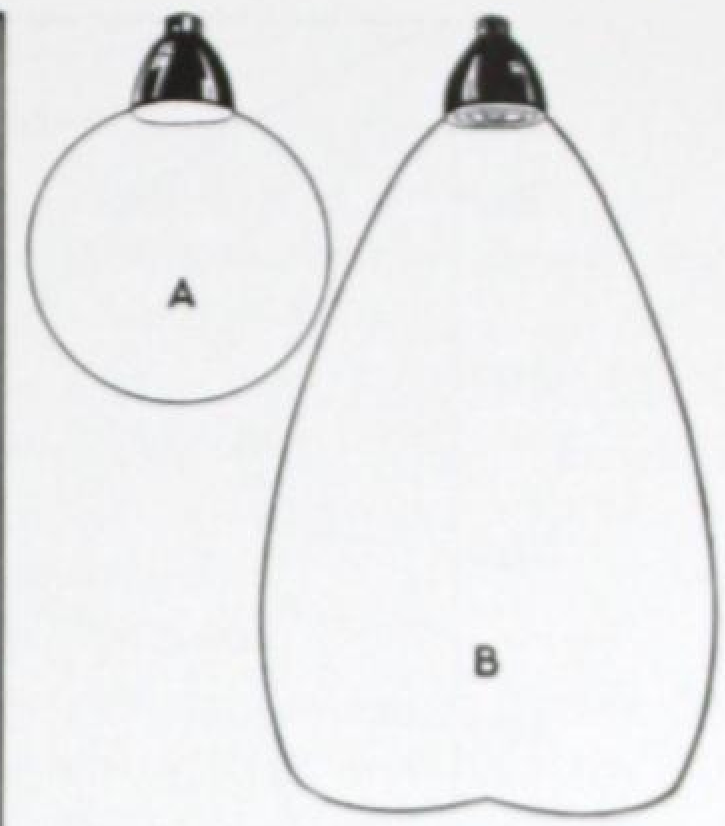


Fig. 11. These two curves for direct units represent equal lumen output. Curve B provides more light directly under the unit, but in curve A, the effect of the large zones near the horizontal is evident.

Lamp and Luminaire Efficiencies

The basic formula for efficiency: $\frac{\text{output}}{\text{input}}$ is expressed for a lamp in terms of its output in lumens (of light) divided by the input in watts (of electric power) or the quotient, *lumens per watt*. The first term may be determined from a candlepower distribution curve or spherical photometer; input watts, from volts x amperes.

The efficiency of a luminaire is expressed by a similar ratio:

$$\frac{\text{Lumens of Luminaire (output)}}{\text{Lumens of Lamp (input)}}$$

In Fig. 12, the lumens of the luminaire total 2959. Since the lamp lumens equal 3700, the efficiency of the luminaire equals $\frac{2959}{3700}$ or 80 per cent.

Lumen Output of Asymmetric Luminaires

To determine the output of non-symmetric or asymmetric luminaires, such as conventional fluorescent units, candlepower readings must be taken in a number of planes and their weighted average obtained for each zone. The zone candlepower multiplied by the zonal constant gives the zonal lumens. The sum of the zonal lumens equals the lumen output of the luminaire.

For a fluorescent lighting unit, candlepower readings are usually taken in five planes, at 0°, 22½°, 45°, 67½°, and 90° from a plane through the luminaire axis. Candlepower values are measured in each plane at 10° intervals (5°, 15°, 25°, etc.). Assuming the five planes are at the angles 0°, 22½°, 45°, 67½°, and 90° and that the candlepower readings at such intervals are designated as A, B, C, D, and E, then their weighted average is obtained by the formula:

$$Cp = \frac{A + 2B + 2C + 2D + E}{8}$$

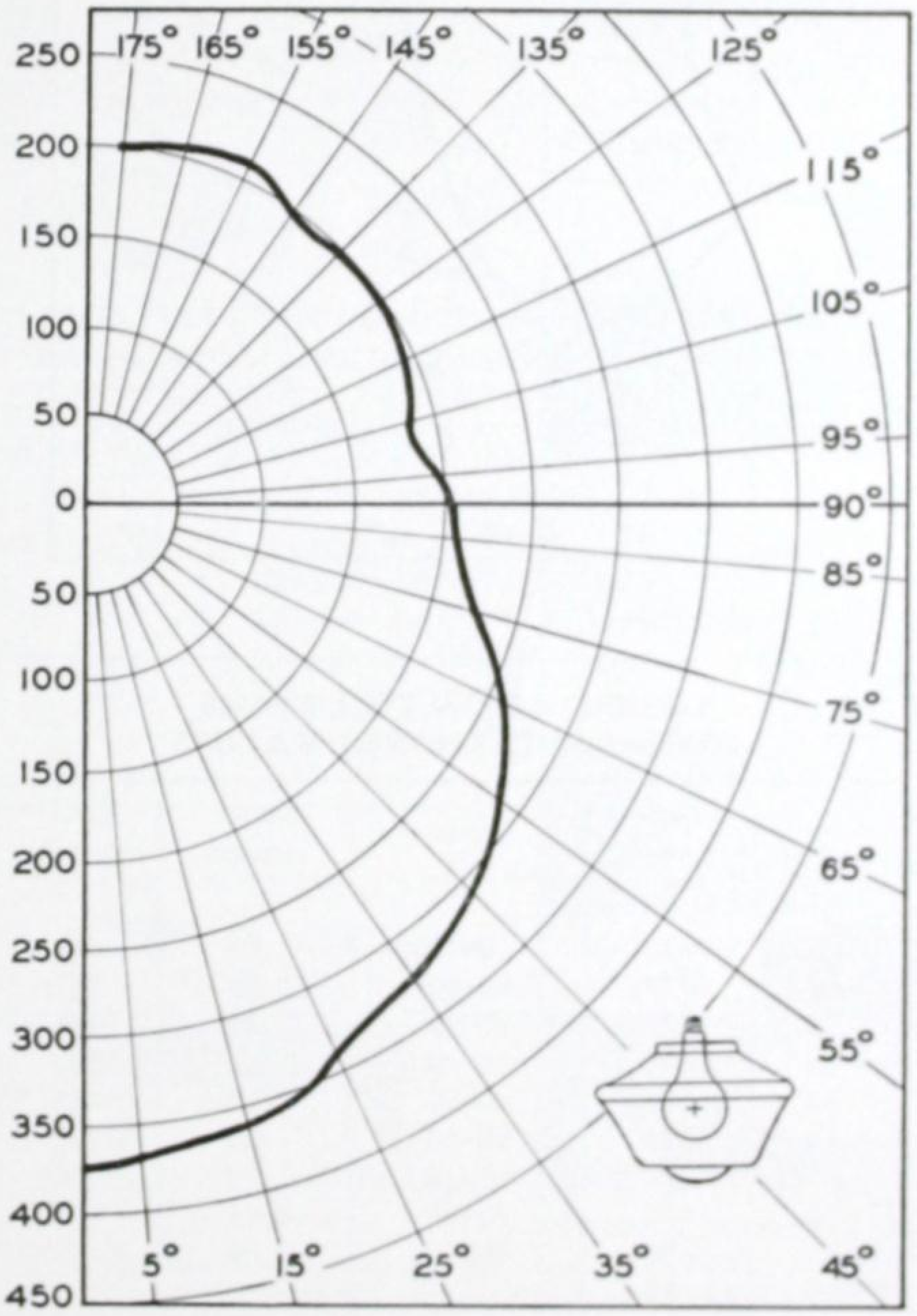
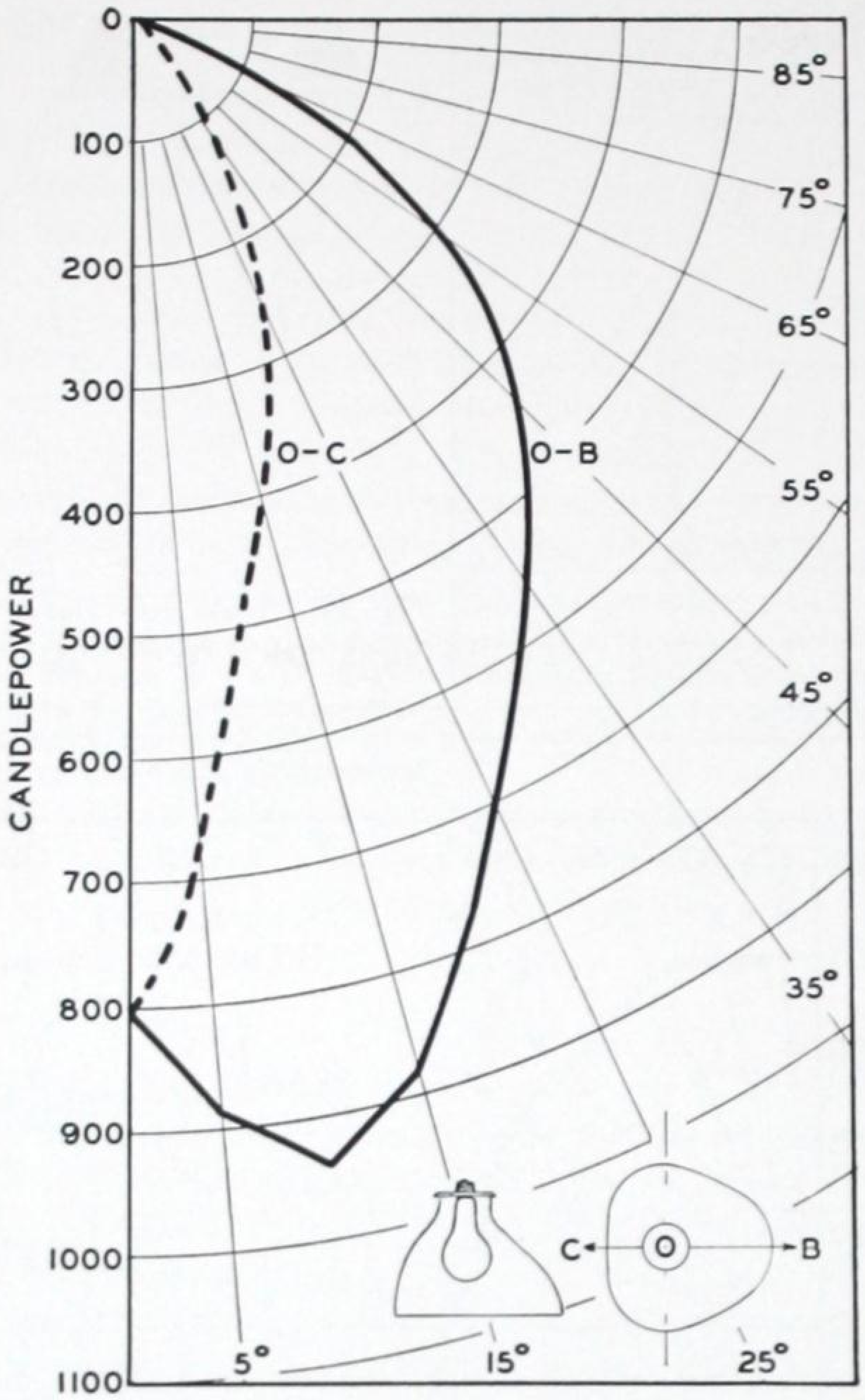


Fig. 12. Candlepower distribution curve of white glass enclosing globe with a 200-watt 3700 lumen lamp.

Zone	Lumens	% Total Lamp Lumens
0–40	503	13.6
0–60	996	26.9
0–90	1713	46.3
90–180	1246	33.7
120–180	630	17.0
0–180	2959	80.0



In some laboratories for similar tests, candlepower readings are taken in three planes only (0°, 45°, and 90°), as in Fig. 15. The candlepower values in A (crosswise) and B (lengthwise) plus twice the values in C (45°) are added. The sum divided by 4 equals the average candlepower.

Similarly, non-symmetric or asymmetric luminaires for filament lamps have such wide variations in candlepower at a given angle about the vertical that an average reading from which to compute zonal lumens cannot be obtained by rotating the unit. Candlepower distribution curves for such equipment are prepared from data obtained in specific planes and in interpreting such curves one must be careful to observe the planes they represent.

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Fig. 14. Candlepower distribution curves of non-symmetrical sources such as show window reflectors vary widely and their interpretation depends upon the specific planes in which they are taken.

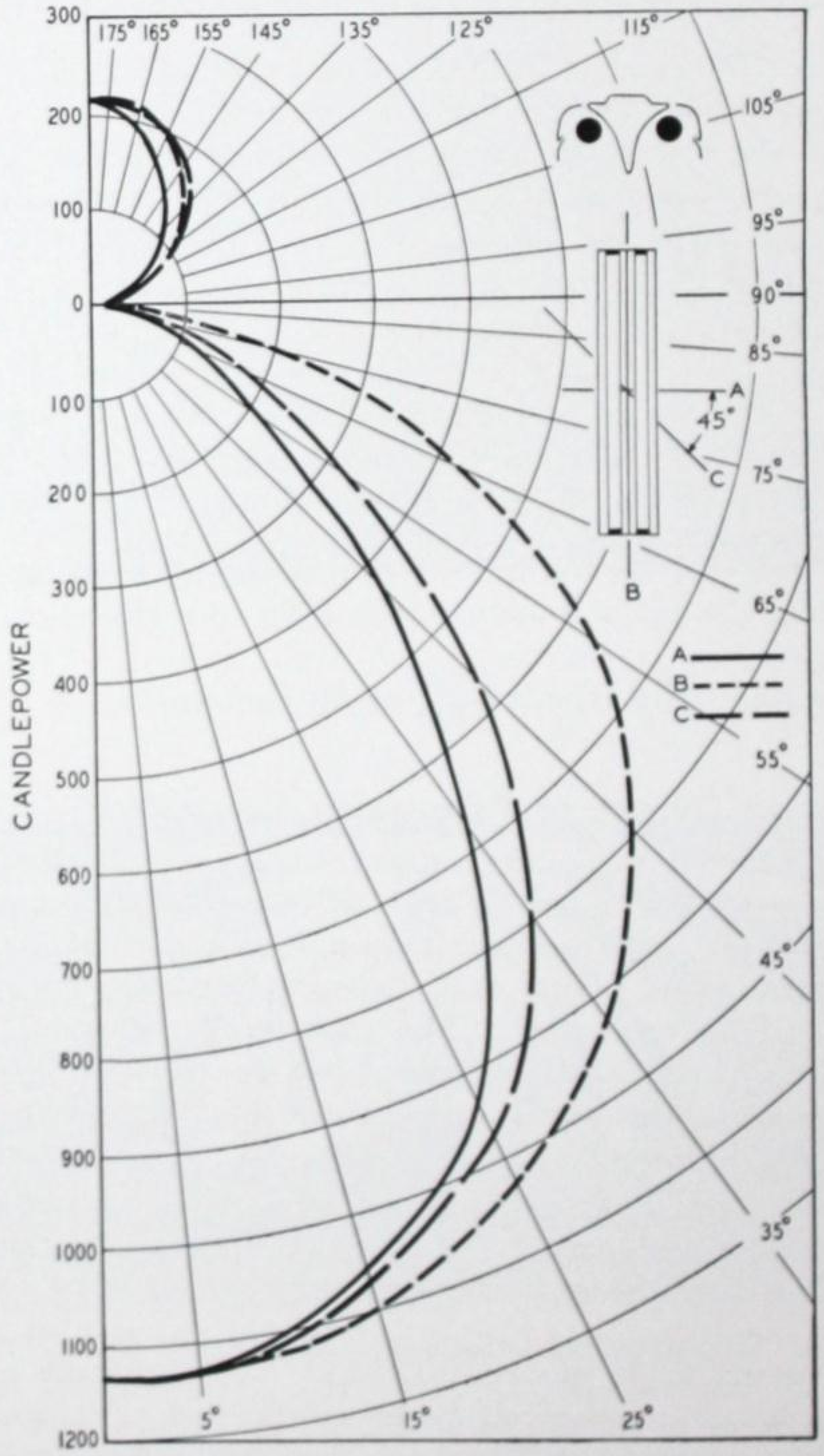


Fig. 15. The average candlepower multiplied by the zone constant gives the zone lumens. Candlepower values at a given angle in curves A & B are added to twice the value in curve C at the same angle. This sum is divided by 4 to get the weighted average candlepower.

COMPUTATION OF LUMENS FROM CANDLEPOWER VALUES

Angle	Candle-power	Zone	Zonal Constant	Zonal Lumens
0	1130			
5	1125	0–10	.10	112
15	1075	10–20	.28	301
25	975	20–30	.46	448
35	802	30–40	.63	505
45	591	40–50	.77	455
55	374	50–60	.90	337
65	232	60–70	.99	230
75	125	70–80	1.06	132
85	38	80–90	1.09	41
90	12			
95	11	90–100	1.09	12
105	26	100–110	1.06	28
115	58	110–120	.99	57
125	89	120–130	.90	80
135	115	130–140	.77	89
145	148	140–150	.63	93
155	174	150–160	.46	80
165	200	160–170	.28	56
175	211	170–180	.10	21
180	214			
			Total Lumens	3077

BRIGHTNESS

Although in light measurements one seems to deal principally with intangible things and quantities, the characteristic of light that has undeniable reality is the factor of brightness. In fact, our ability to see is largely the result of our appraisal of such brightness or brightness differences between objects in the field of view. For example, the visual task of reading this page is possible because the paper reflects light toward the eyes and its brightness is greater than that of the ink.

Brightness is produced in three ways: first, by a self-luminous object, such as the sun, a star, or a lamp bulb, from which source the generated light energy comes directly to the eyes; second, by light energy transmitted through objects, such as clouds over the sun or a translucent luminaire such as a white glass globe. The third source of brightness is by reflection, such as the moon and the sky which receive light from the sun, the surface of a reflector in a luminaire, and most of the surfaces and objects we see in everyday activities.

Brightness Units—the Footlambert

The unit of brightness commonly applied to so-called "perfectly diffusing" surfaces of comparatively low brightnesses is defined in terms of the lumens emitted per square foot. This unit is called the footlambert (fL). The brightness in footlamberts of a wall in a room is related to the footcandles of illumination upon it. For example, if the wall is uniformly lighted to 20 footcandles (lumens/sq. ft.) and reflects half of them, its brightness is 10 lumens per square foot or 10 footlamberts.

A brightness of one footlambert may be visualized by assuming the unit sphere of Fig. 4 to be perfectly transmitting and hence its outer surface would be lighted to a brightness of one lumen per square foot or one footlambert.

It should be noted that from the definition of brightness the *projected* area of a surface or object is considered, not its actual area. A luminous sphere, for example, has an apparent or projected area equal to that of a disk of the same diameter. The unit sphere of Fig. 4 with a diameter of 2 feet, or a radius of 1 foot, has a projected area of πr^2 or 3.14 sq. ft. or 452 square inches. Since the source is 1 candlepower, its brightness is 1/3.14 candles per sq. ft. or 1/452 c/in². By definition, its brightness is also one lumen per square foot or one footlambert, hence one footlambert equals 1/452 c/in², or conversely, 1 candle per sq. in. equals 452 footlamberts.

Brightness is sometimes easier to picture as the "concentration of candlepower." The brightness unit for sources of high brightness is the *candle per square inch* (c/in²). The brightness unit commonly applied to sources of *low* brightness is the *footlambert* (fL). We are more often interested in such sources and if the luminaire is spherical and the lamp candlepower is known, the formula is very simple:

$$\text{Brightness} = \frac{\text{Candlepower x Efficiency}}{\text{Globe Radius}^2}$$

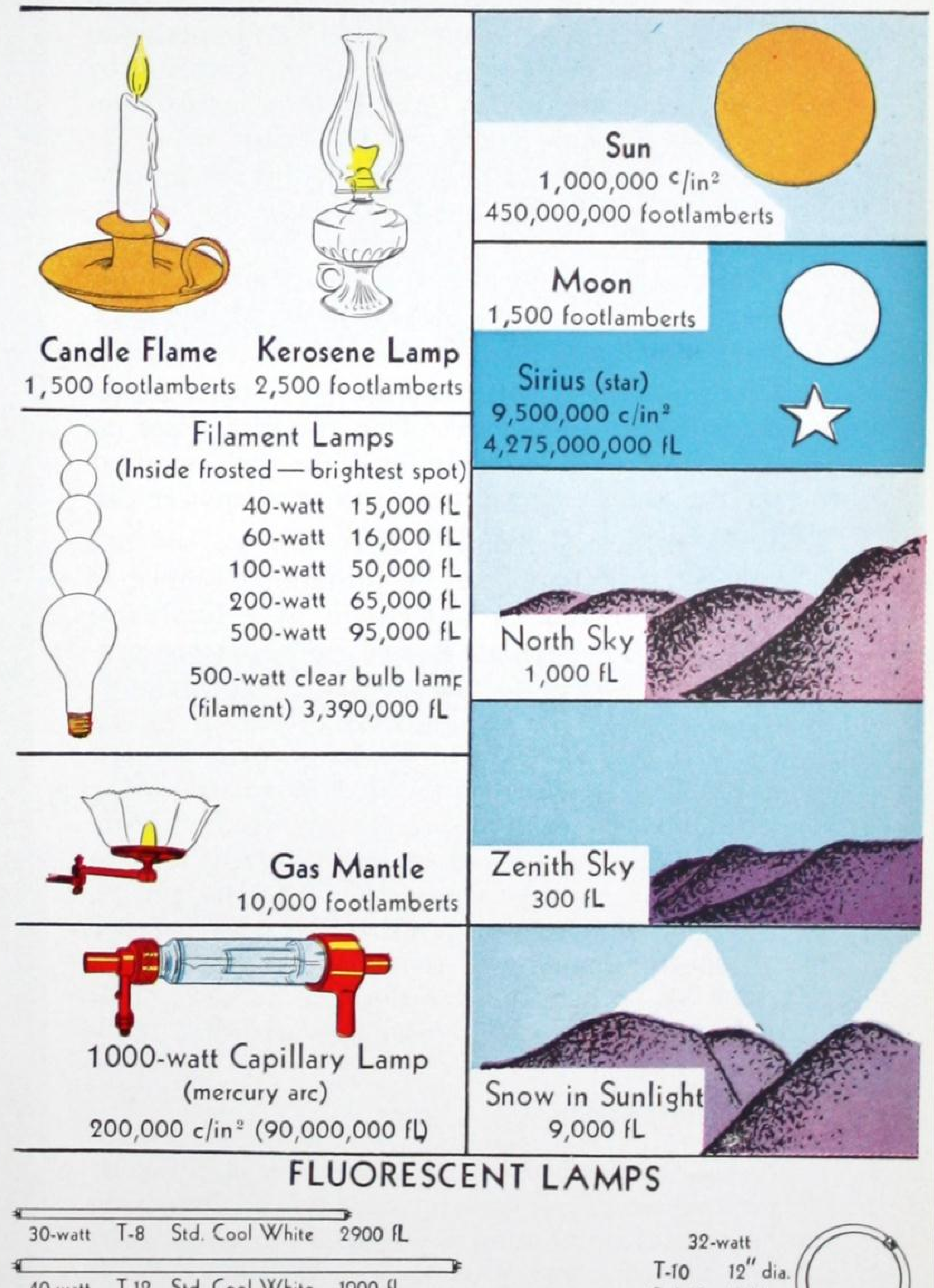
The brightness is in footlamberts when the Globe Radius is in feet.

Thus a spherical globe with a 1 ft. radius (24-inch diam.) uniformly bright and 80 per cent efficient, containing a 1000-cp lamp has a brightness of:

$$\text{Brightness} = \frac{1000 \text{ x } .80}{1^2} \text{ or } 800 \text{ fL.}$$

To express this in candles per square inch, divide by 452. This globe has a brightness of 800/452 or 1.8 c/in².

TABLE 2. BRIGHTNESS OF LIGHT SOURCES



Fluorescent lamp values in November 1955

PART III—PHOTOMETRIC LABORATORY MEASUREMENTS

Prior to the invention of the photronic or light-sensitive cell, most instruments for the measurement of candlepower and brightness employed the principle of visually balancing two adjacent fields. These were viewed simultaneously in mirrors at angles, as in the photometer of Fig. 16.

More modern instruments contain a Lummer-Brodhun cube, in which two prisms received light from the sources to be compared. The beams are refracted by two prisms to parts of a pattern.

Laboratory photometers of the type employing this device, were used for obtaining candlepower distribution curves of lighting equipment. The luminaire to be measured was mounted on a shaft and revolved by a motor mechanism. The light from a comparison lamp passed through baffles, the illumination on the comparison screen varied by moving the comparison lamp. The operator balanced the comparison source against the light from the luminaires. From the readings obtained at 10° intervals, the average zonal candlepowers were obtained and the efficiency of the luminaire calculated.

This general type of photometer has been superseded by direct-reading types of instruments. Since no visual balance needs to be obtained, the time required to take the necessary readings for a candlepower distribution curve is greatly reduced.

As mentioned previously, a minimum distance of five times the maximum dimension of a luminaire or light source is commonly used in laboratory testing. At this distance, the error is approximately ½ per cent, as shown in the curve of Fig. 21. The testing of large fluorescent luminaires introduces new space problems. The length of a luminaire using 96-inch lamps, for example, requires a distance from cell to the unit of 40 feet or more. Such a space requirement is not easily met in most laboratories. One method of overcoming this obstacle is to cover half of the luminaire with screens, reading one half and then the other, then adding the values. This method is convenient and reasonably accurate.

Mirror Photometer

Another method of space conservation is shown in the direct-reading photometer of Fig. 17. The conventional horizontal dimension of 10 feet has been reduced by using two mirrors. Light from the test luminaire is directed to one mirror and thence to the other and to the cell. The light path from luminaire to cell is 10 feet. The galvanometer is connected to the cell and reads directly in candlepower by the application of constants determined by first reading secondary standard lamps whose candlepower values are known.

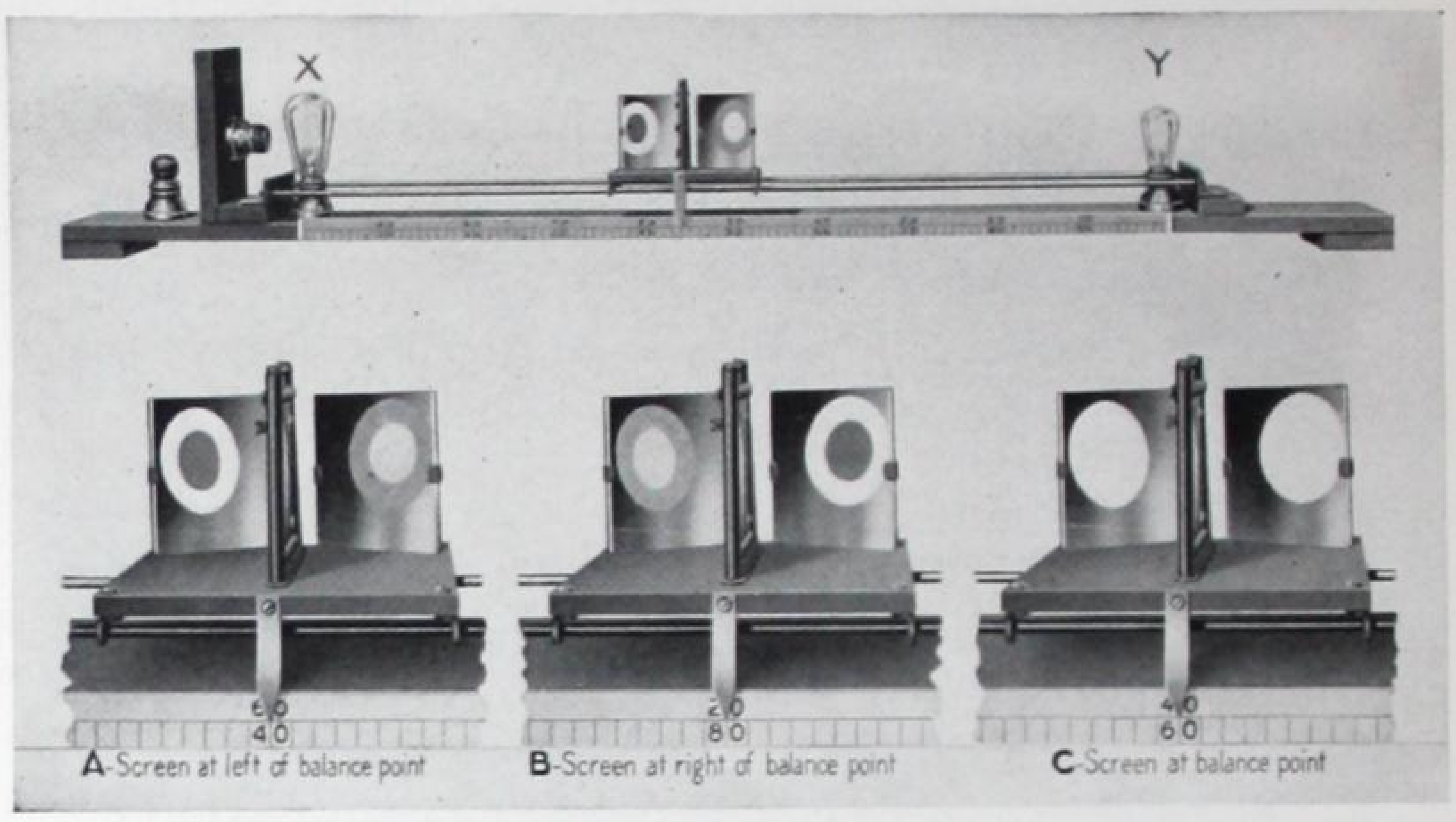
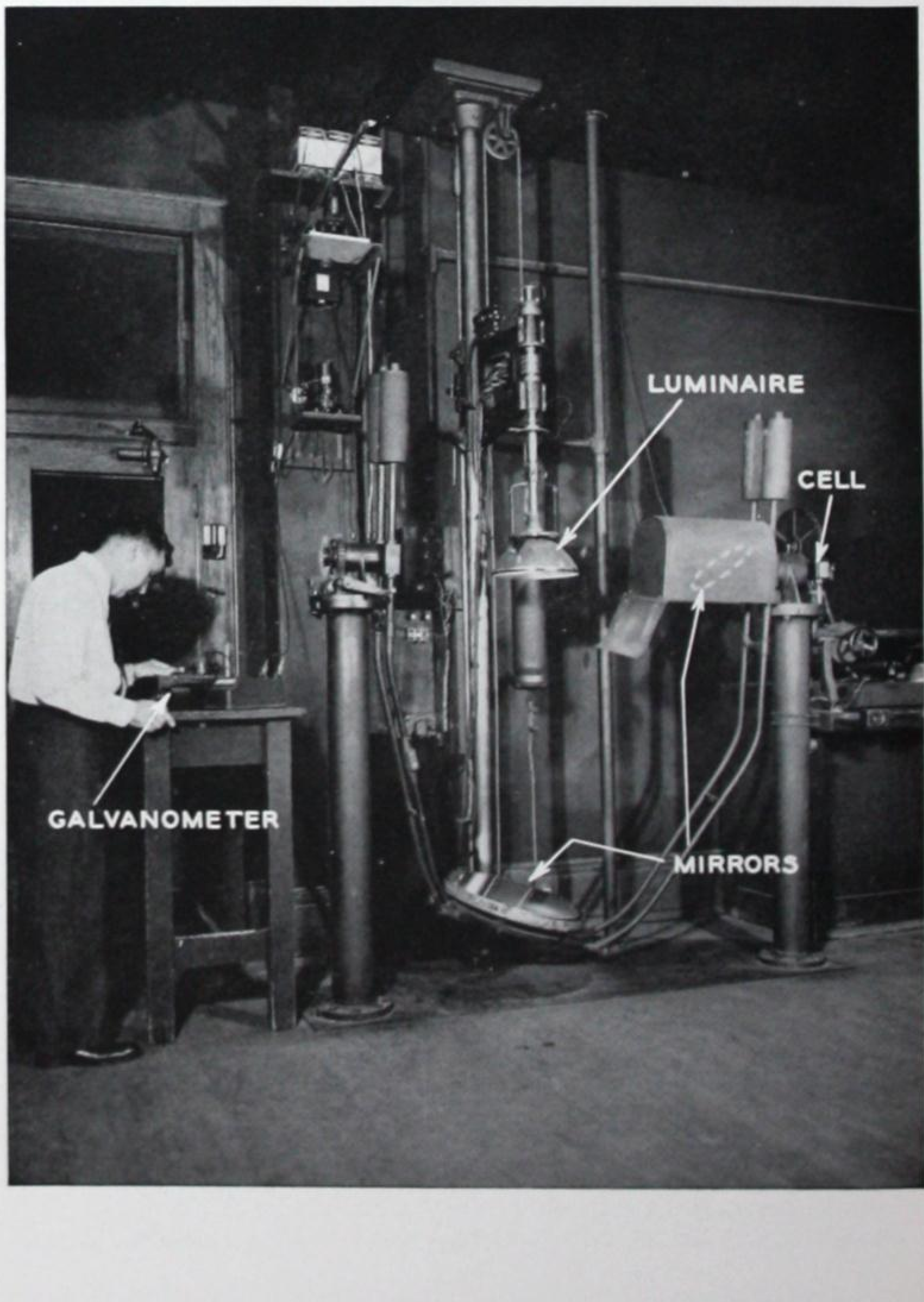
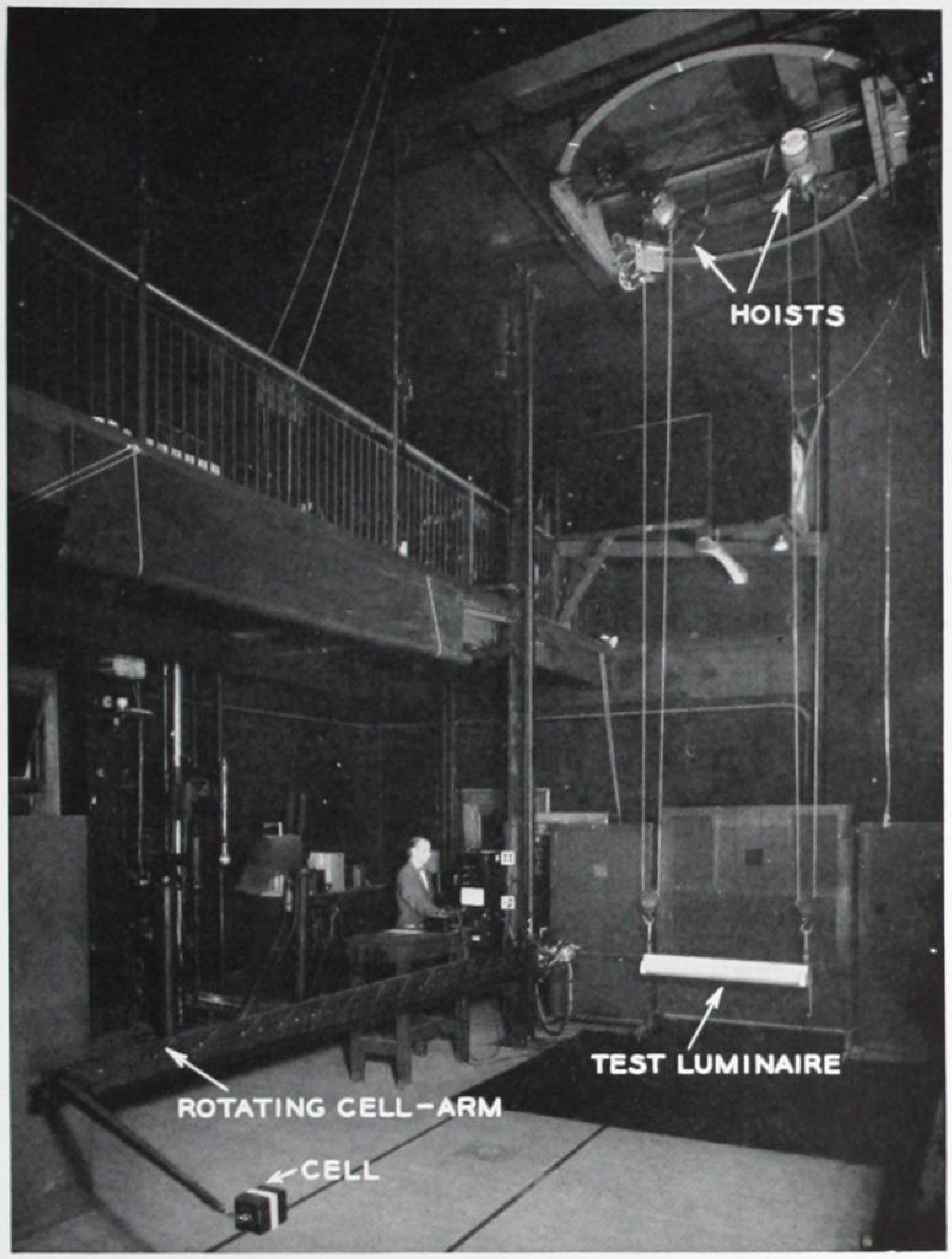


Fig. 16. The Bunsen photometer contains a movable screen; its center spot is translucent. If the light from Lamp X on the spot is greater than that from Y, the spot appears dark as in A. If the reverse is true, the spot appears brighter than its surroundings as in B. At C, a balance point is reached and the spots disappear. The two sides of the screen are viewed simultaneously in the mirrors placed at angles.

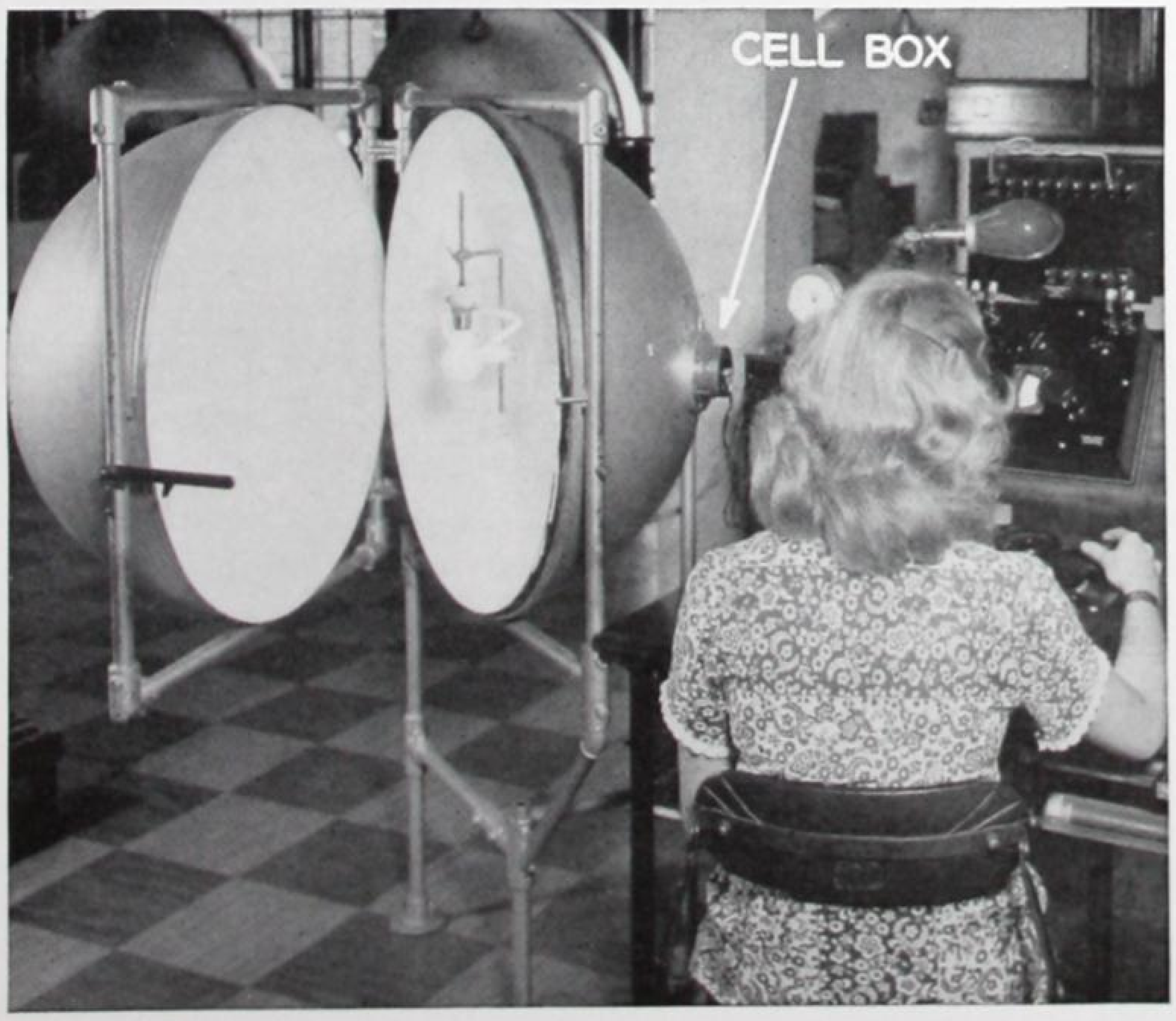
Fig. 17. The mirror photometer conserves space by reducing the luminaire-to-cell distance by reflection.

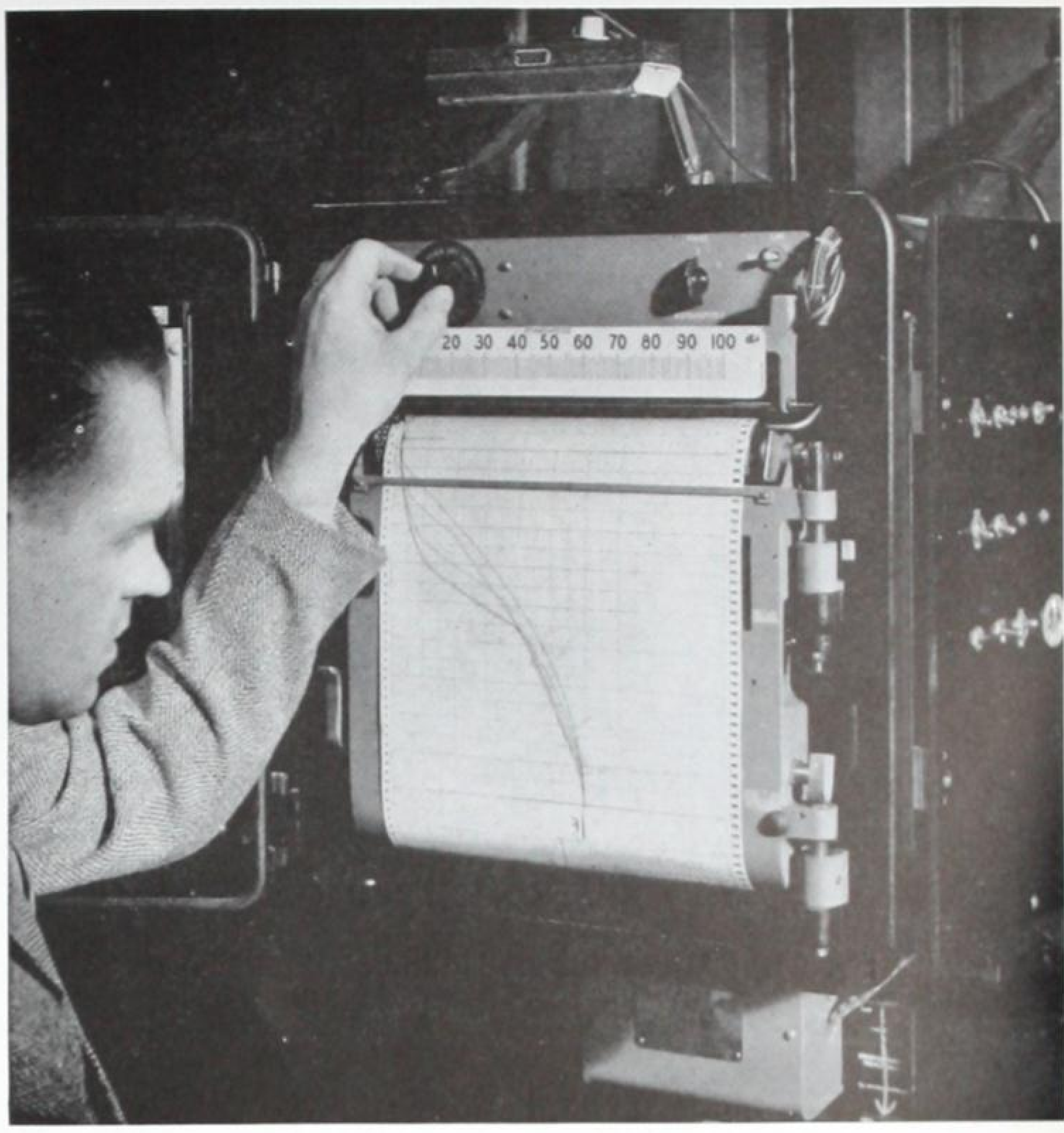




▲ Fig. 18A. With this semi-automatic recording photometer, a curve in one plane can be taken on a luminaire in about one minute.

▼ Fig. 19. This barrier-layer-cell photometer employs an integrating sphere. The cell box contains the photocell and suitable filters.





▲ Fig. 18B. Closeup of recording instrument of semi-automatic photometer. The inked lines are traces of the candlepower values of the luminaire as the cell is moved in an arc about it.

▼ Fig. 20. The 120-inch sphere photometer is one of the largest in existence. It is principally used for measuring the light output of long fluorescent lamps.

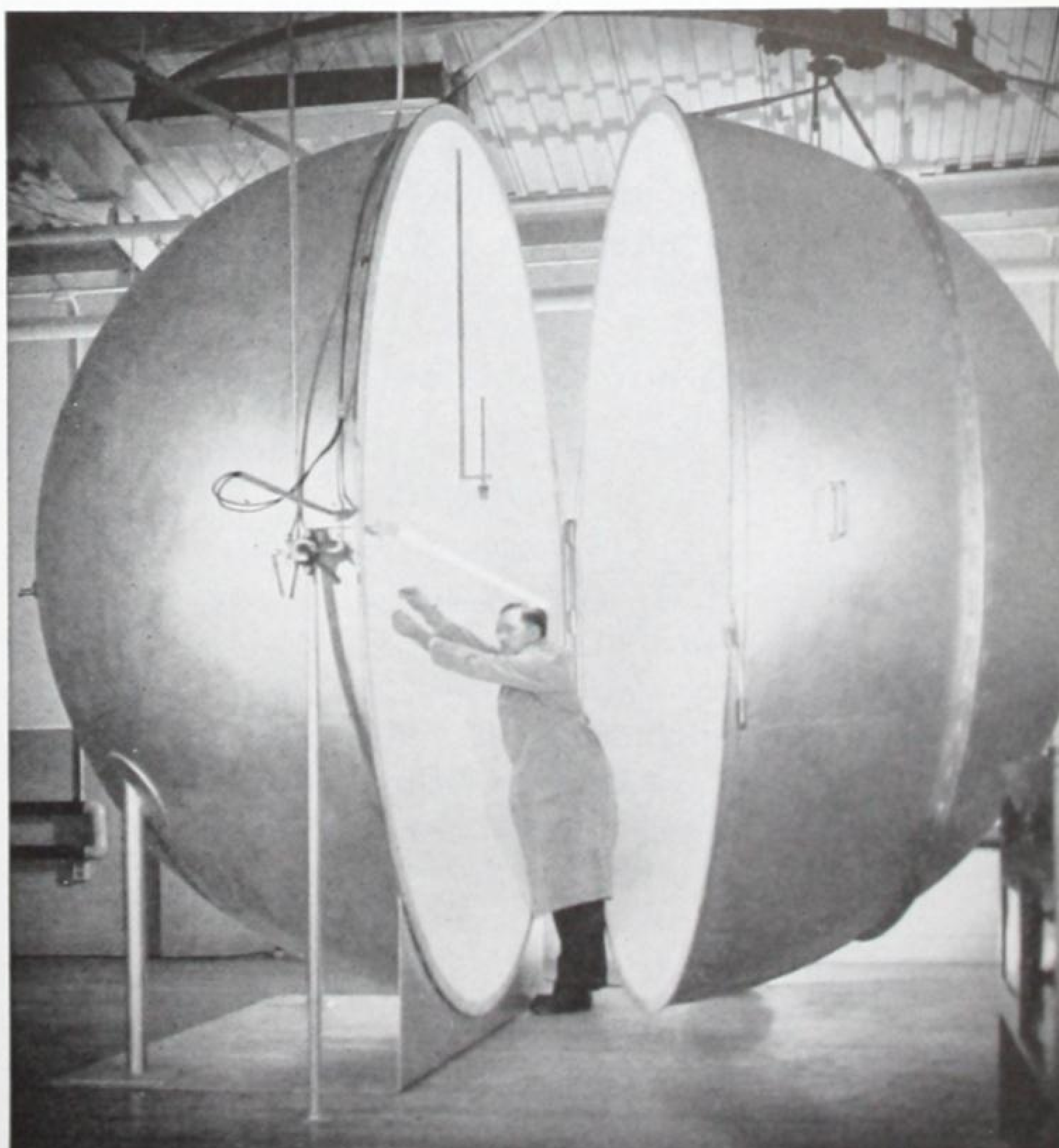


Fig. 21. Effect of photo cell distance on candlepower measurements.

A modern semi-automatic recording photometer is shown in Fig. 18A. Its principal parts are the recording instrument (shown in Fig. 18B), the 20 ft. cell-arm (foreground), and a circular-track support mechanism with two electric hoists (on ceiling). Once the luminaire has been put in place, a test in one plane can be run in about one minute.

By covering the light-sensitive cell with suitable filters, readings for plotting distribution curves for other radiant energy sources such as sunlamps and germicidal tubes, may be obtained. Their interpretation is, of course, predicated on the needs in each field of application.

Photocell Integrating Sphere Photometer

A modern laboratory photometer for measuring light output is the barrier-layer cell photometer shown in Fig. 19. The instrument employs an integrating sphere which is made in two halves so supported and hinged that one side may be swung open easily by the operator. The socket for the test lamp is placed so that the light-center of the source coincides with the center of the sphere. The interior wall and internal parts are painted with several coats of flat white paint and then with two or three coats of special white sphere paint which gives them an extremely mat finish. Spheres vary in size from one inch to 30 inches in diameter—for miniature and low-wattage large lamps—up to 120 inches for high-wattage and long sources such as fluorescent lamps (Fig. 20).

A circular aperture (approximately three inches in diameter for large spheres) located in the wall of the sphere contains a white glass disk. The light on this window is equal to that received by any other similar portion of the sphere interior due to cross-reflections in the sphere and therefore the light on the window is proportional to the total light generated by the test source. A metal baffle is interposed between the window and the lamp under test so that the light from the test lamp does not fall directly on it.

The photocell which is equipped with suitable filters to produce a spectral sensitivity comparable to that of the eye, is contained in the cell box, adjacent to the window, and is connected to a circuit containing a sensitive galvanometer. Batteries in an external circuit are connected with potentiometers and oppose the cell current; by balancing the two, the galvanometer is brought to zero and the values read.

In operation, the switches are closed and a lamp lighted in the sphere for about 15 minutes when starting up cold, to overcome any slight cell fatigue which may be encountered. The photometer is checked periodically by placing a standard lamp in the sphere, applying the proper voltage to it, and balancing the galvanometer to the zero position. The lamps to be read are then successively placed in the sphere and measured. By proper calibration of the scale for the meter, the mean spherical candlepower or lumens can be read directly.

The design of small spheres 36 inches in diameter or less is similar to the larger models. In the 36-inch sphere, values as low as three candlepower or 38 lumens can be measured satisfactorily. The choice of the sphere size is largely a matter of convenience.

Correction Filters

The relative efficiency of the eye in responding to light of different colors is commonly shown as a function of wavelength of the color of the light. Slight variations exist in this response even between persons of normal vision and visual photometry is therefore critical and relatively less dependable. Conventional photocells are similarly deficient; they do not coincide with the eye characteristic. Cells of the selenium type are in general more sensitive to the blue and red regions than is the eye, as indicated in Fig. 22. One method of correcting the error is to calibrate the scale of the meter under a standard light source of known color temperature and then to determine the correction factors to be applied when the meter is used to measure illuminants of other spectral character. The generally accepted light source is a tungsten filament

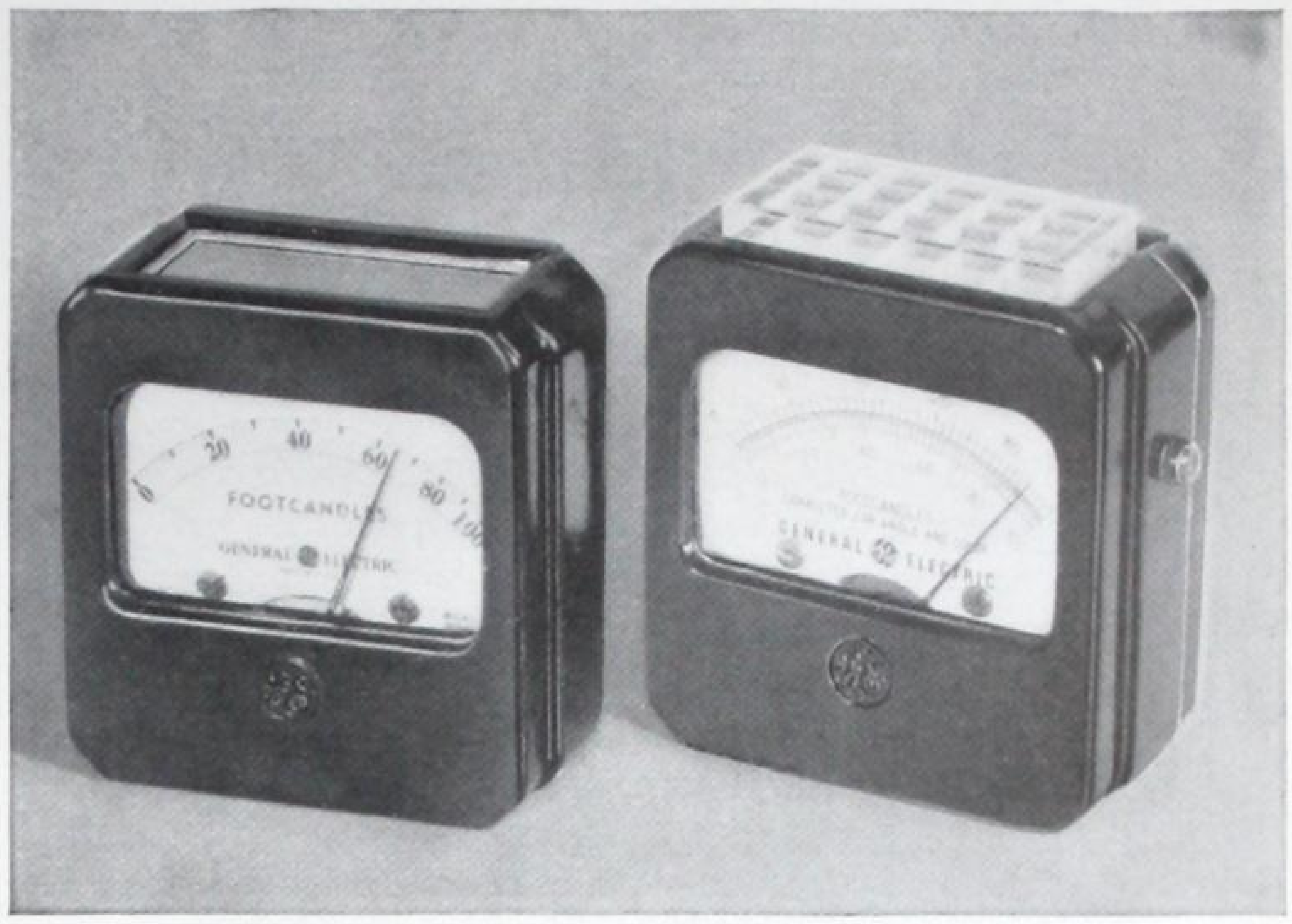


Fig. 23. Left—G-E light meter. Right—The top lamination of the cell of this c/c lightmeter employs a green filter for color correction and a plastic lens for angular correction. Its color response almost exactly matches the eye curve of Fig. 22. The special plastic lens refracts light from grazing angles into the cell, which increases the accuracy of this type of instrument (cosine correction). See discussion, pages 19 and 20.

lamp operating at 2700° K (color temperature). The correction factors for other illuminants such as mercury, neon, and other sources are determined by comparing the spectral curve of a given cell with the known curve of the illuminant. This involves considerable mathematical calculation but once the factors are obtained, they are sufficiently accurate for many purposes (see Table 3, page 20).

Since the relative sensitivity curve of most light-sensitive cells lies above the eye curve at all wavelengths, colored glass filters suggest themselves as a means of making the cell coincide with the eye curve.

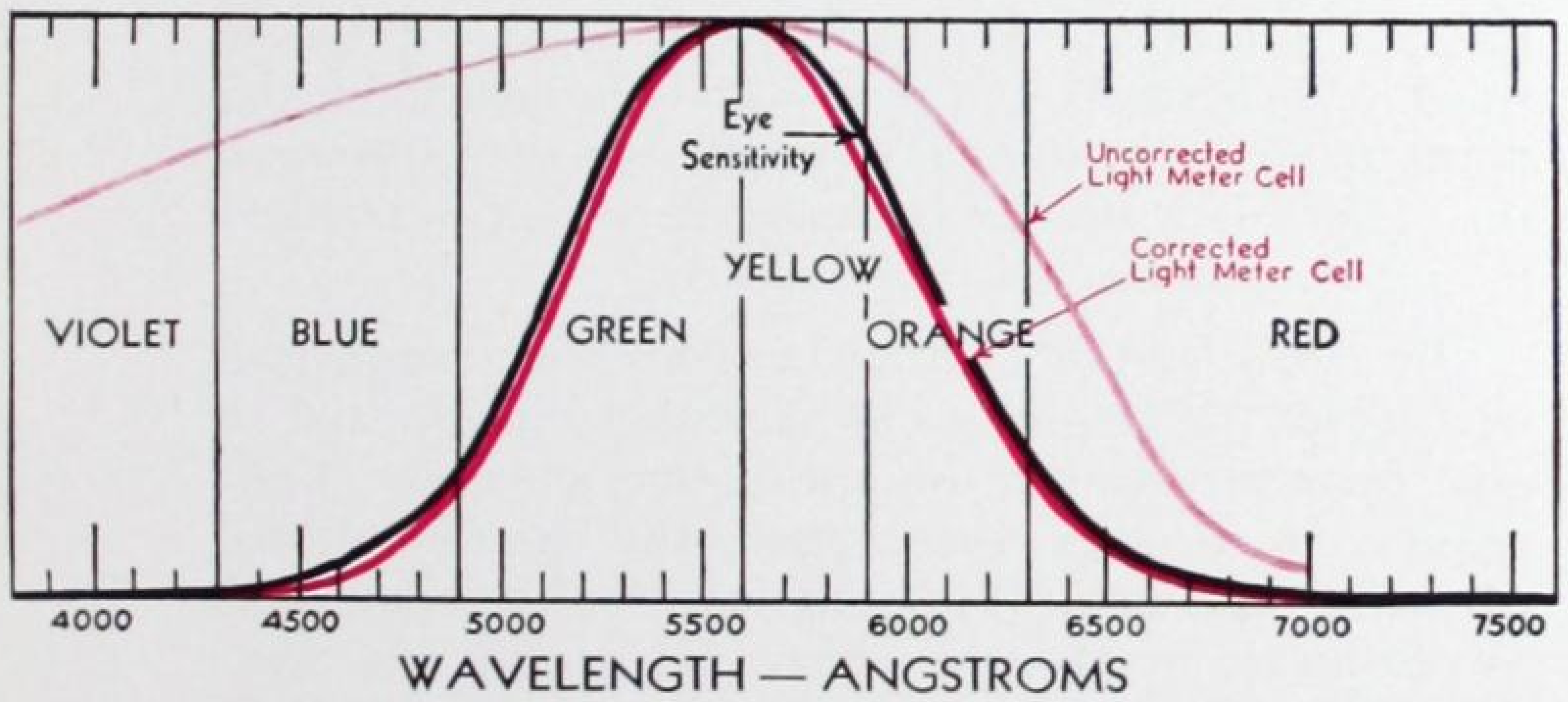


Fig. 22. Cells of the selenium type are in general more sensitive to the blue and red regions than is the eye. They are used in the light meters of Fig. 23.

The use of filters is a most satisfactory solution for correcting cells. The sensitivity curves of the eye and a corrected cell are shown in Fig. 22. However, the cell output is relatively low, that is, only a few microamperes are available from each cell and the usual colored glasses employed absorb light radiation to a relatively high degree. There are three principal ways to compensate for this. One is to use a more sensitive microammeter, another is to build up the current by using several cells connected in parallel. A third method is to utilize a plastic filter of high transmittance with a surface pattern to reflect more light into the cell. This method is used in the c/c lightmeter of Fig. 23.

Angle of Incidence and Other Factors

Cells of conventional pocket-type light meters (Fig. 23), are covered with clear glass plates for mechanical protection. Light which strikes the plate at oblique angles does not contribute its proper share in deflecting the needle of the microammeter. This characteristic is corrected in the c/c lightmeter by replacing the cover glass with a plastic lens plate. (Fig. 23, right.) This plate has etched sides and a special grid pattern on its under surface. The combination corrects for the non-symmetry of the rectangular cell.

Accuracy in photometric measurement depends upon numerous factors not ordinarily evident in a casual visit to a laboratory. One of these is the provision of an alternating current supply of constant voltage which is characterized also by its constant frequency. This is particularly important in the testing of gaseous conductor lamps.

The testing of fluorescent light sources introduces other factors of importance. In such testing, it is necessary to operate the lamps at least 20 minutes before taking readings; it is usual practice in laboratory procedure to employ an initial warming-up period of 30 to 60 minutes so that lamps and auxiliary equipment are brought up to a stabilized condition. In addition, it is common to operate new fluorescent lamps 100 hours, before using them for test purposes because their light output is reduced rather rapidly during the early hours of this initial period. Moreover, for this same reason, it is general practice to list the initial light output of fluorescent lamps at the lumens generated at the end of 100 hours of operation. Similarly, tungsten filament lamps have a small original "hump" in output and new lamps are commonly burned for about 10 hours before being used for working standards or test.

Brightness Measurements

One method formerly utilized to measure the brightness of luminaires consisted of covering the luminaire with a black opaque screen with a one-inch square opening, placed at the point on the surface to be measured. The candlepower of the light at this angle was then measured by conventional methods and since the light flux came from one square inch, the brightness was in terms of candles per square inch (Fig. 25).

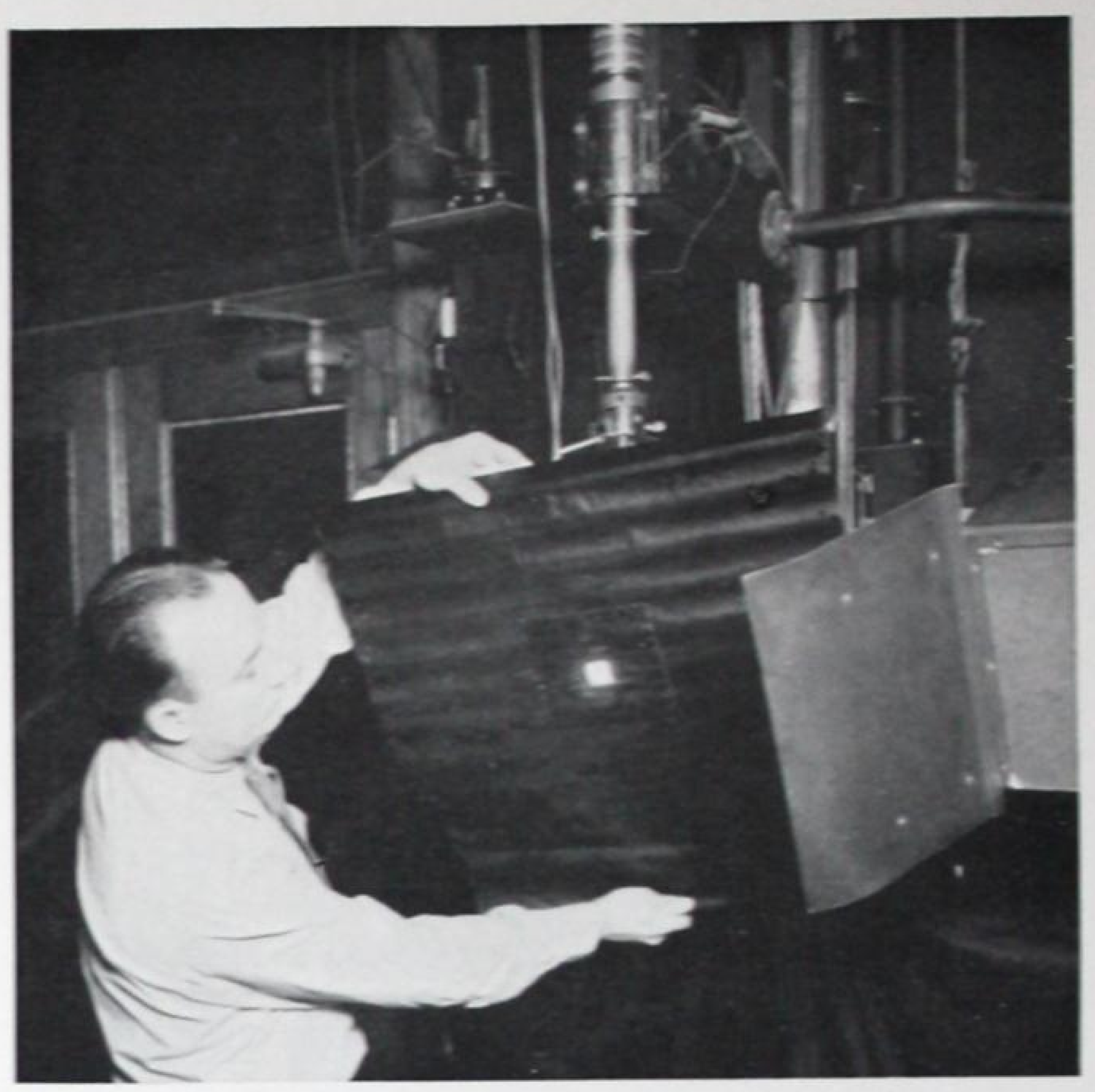


Fig. 25. Measuring the brightness of an enclosing globe. The opening in the opaque screen is one square inch.

Another method is to use the General Electric brightness meter as discussed on page 23. A special instrument used solely for measuring the brightness of fluorescent lamps consists of a housing placed over the part of the lamp to be measured, several light-sensitive cells, and a rheostat. The meter reads brightness directly in footlamberts.

Measuring Reflectance and Transmittance

Accurate readings of reflectance and transmittance may be made with the General Electric reflectometer called a light-sensitive cell reflectometer. The meter employs an integrating sphere, finished on the inside with a white mat surface. On the side of the sphere, slightly above the center line, is a tube containing a lens system and a projection lamp. By means of this projector assembly, a beam of light is directed to an area about two inches in diameter on the opposite wall of the sphere. Two light-sensitive cells are located in the sphere wall on either side of the beam and normal to the beam axis. The cells are connected in parallel to a microammeter located on the top of the sphere. Brightness of the sphere is indicated by the pointer on the scale of the meter. In the bottom of the sphere is a three-inch aperture which is covered by any flat surface to be measured.

Fig. 24. By inserting a sample of glass between the sphere of the light-sensitive cell reflectometer and the light-source (lower) sphere, transmittance can be determined. The instrument is used by paint, plastics, glass, furniture, and luminaire manufacturers.

By means of the rheostat in series with the projection lamp, the brightness of the sphere is adjusted to give full-scale reading on the meter when the light beam is on the side of the sphere and the test surface covers the aperture. The scale is in 100 divisions, and the full-scale reading is referred to as 100 per cent. After this adjustment, the projector arm is rotated 180° which places the light beam on the test surface. The sphere is now illuminated by the light reflected from the surface and the pointer indicates the per cent reflection factor directly.

In measuring transmission factors with the light-sensitive cell reflectometer, the light beam is replaced by an external light source consisting of another sphere with a white mat finish and a lamp located at its center. The second sphere has a one-inch opening at the top which in assembly is centered in the aperture of the reflectometer sphere, as shown in Fig. 24.

A full-scale setting is made on the microammeter as before with the lamp in the lower sphere turned on but without the test sample in position. The sample is then inserted between the two spheres and the light transmitted through it illuminates the upper sphere. A baffle in front of the lamp prevents direct rays from striking the sample. The resulting reading equals the diffuse transmittance in per cent.

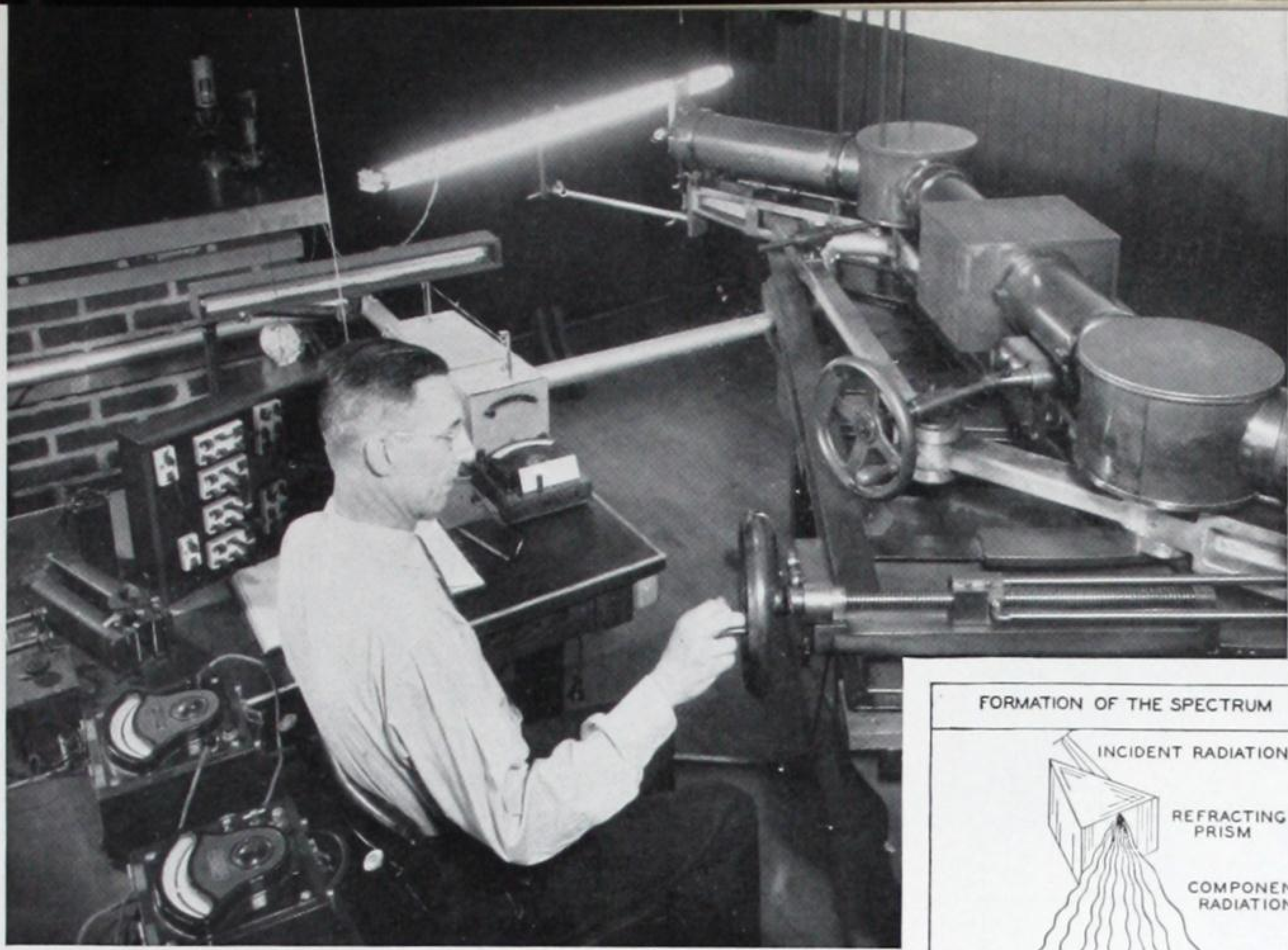


Fig. 26. The spectrophotometer makes measurements of spectral intensities in bands of 1/10,000 of the visible spectrum length, establishing color standards with extreme exactness. It contains a quartz monochromator. The instrument is shown measuring a fluorescent lamp to be used as a standard in a lamp factory.

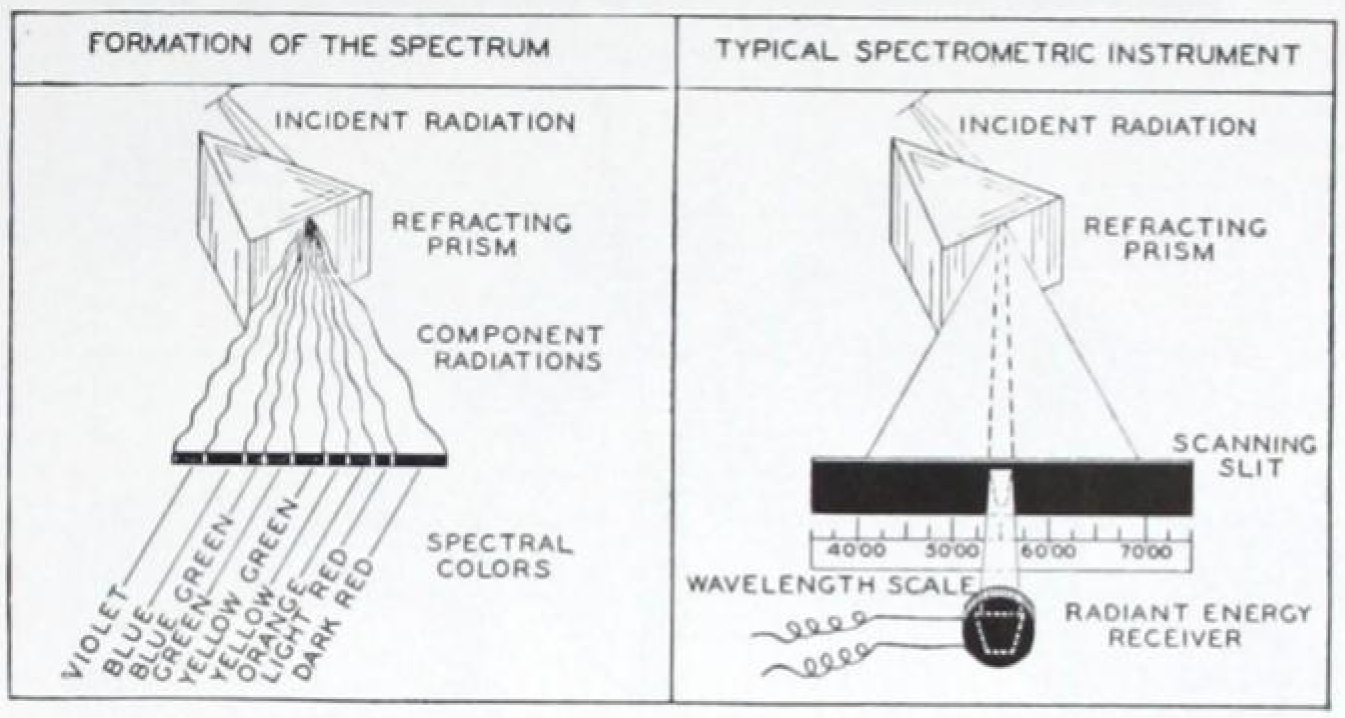


Fig. 27. The spectrophotometer measures the energy in a series of bands by means of a scanning slit as illustrated.

MEASUREMENTS OF SPECTRAL ENERGY

When a wavelength analysis of the visible energy from a source of light is obtained by means of a spectrophotometer and plotted as shown in Fig. 28, the curve is called a *spectral distribution curve*. A similar curve of the light reflected by an object is called a *spectral reflectance curve* and of a transmitting material, a *spectral transmittance curve*. Use of the General Electric recording spectrophotometer makes it possible to obtain such data very quickly. Instruments of this kind are used by paint and dye manufacturers in making accurate spectral analyses of test samples and products. The inaccuracies of visual analysis are eliminated. As shown in Fig. 27 the spectrophotometer measures the energy in a series of bands by means of the scanning slit illustrated. A curve may be plotted from the data in the same way that a candlepower distribution curve is plotted from individual points measured at the center of zones.

Energy of wavelengths shorter than about 4000 Angstroms (violet) and of wavelengths longer than about 7000 Angstroms (dark red) is not visible. Spectral curves for visible energy are usually plotted from 4000 to 7000 Angstroms from left to right. In Fig. 28 spectral distribution curves are shown of four light sources evaluated to equal footcandles. In Fig. 29, germicidal and drying lamp "relative energy" curves and the sun's radiation reaching the earth are shown.

When the visible spectrum of a white fluorescent lamp is scanned with the spectrophotometer, an occasional band is considerably brighter than adjacent ones. The reason is evident from the fact that the light emitted by a fluorescent lamp consists of a con-

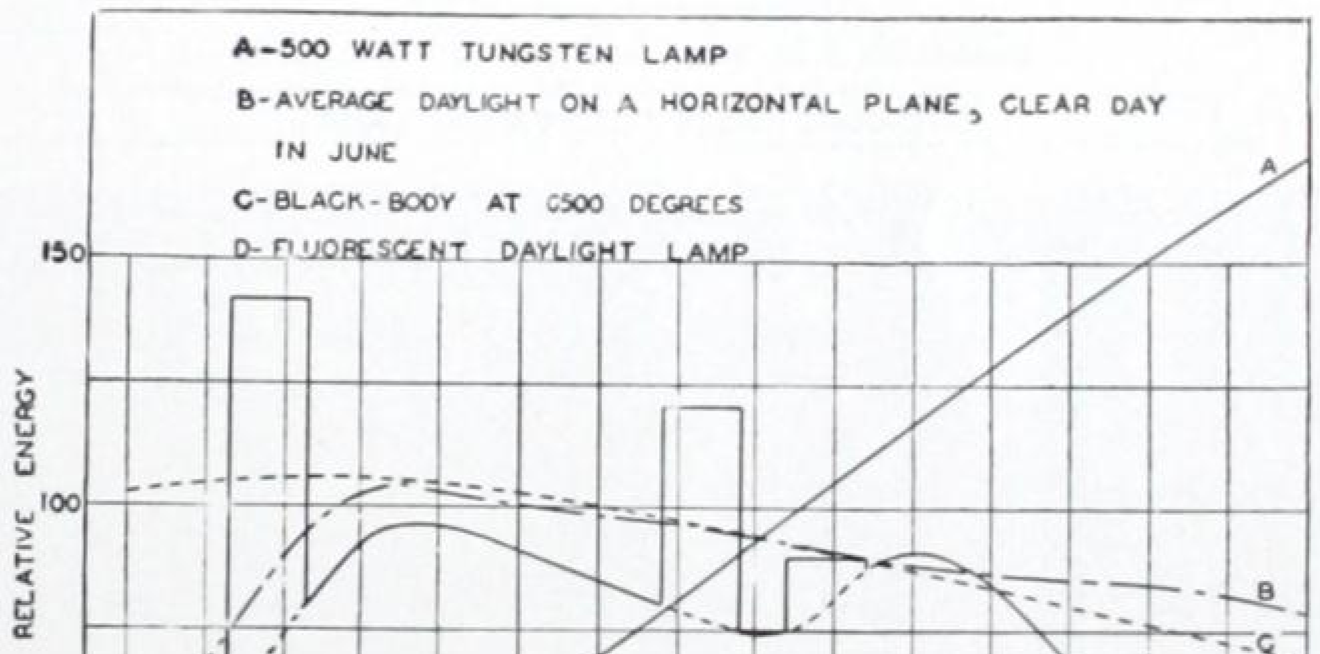


Fig. 28. Spectral energy distribution for four light sources, all at equal footcandles or lumens.

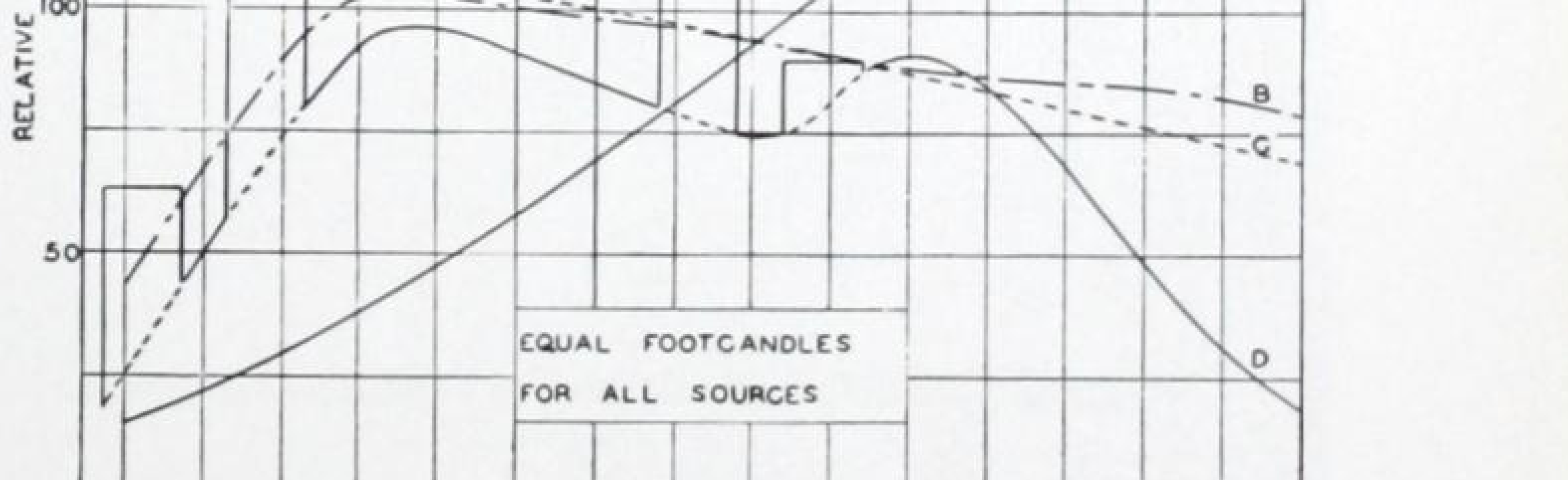


Fig. 29. Relative energy of germicidal and drying lamps and the sun's radiation.

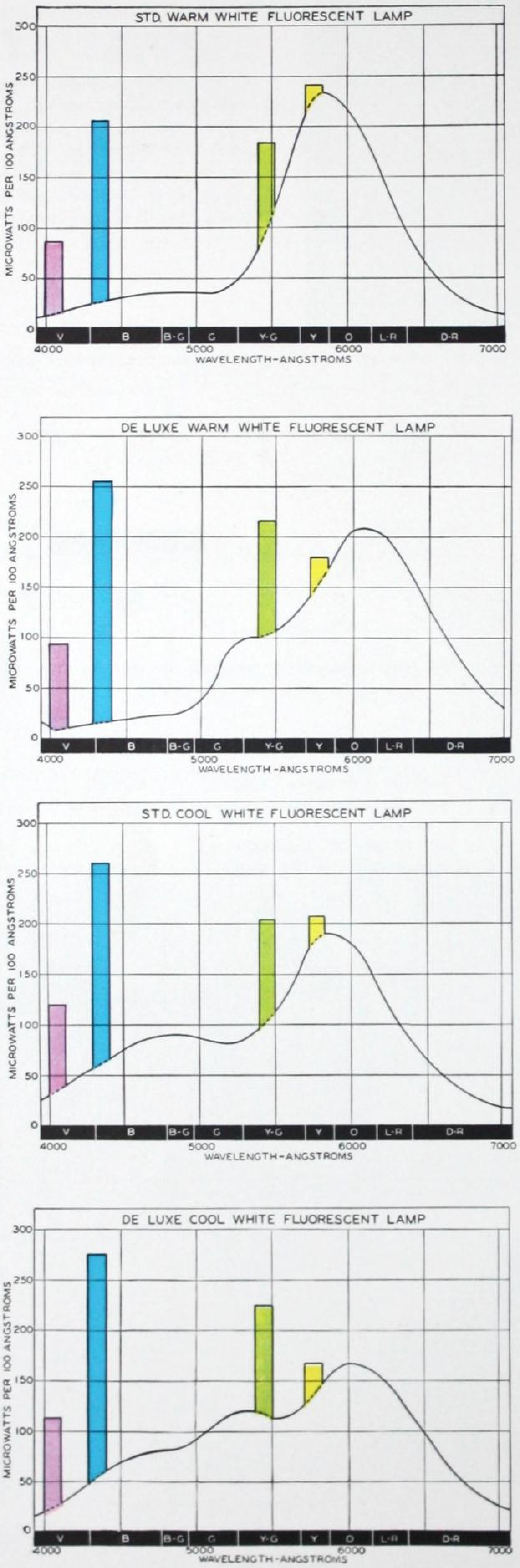


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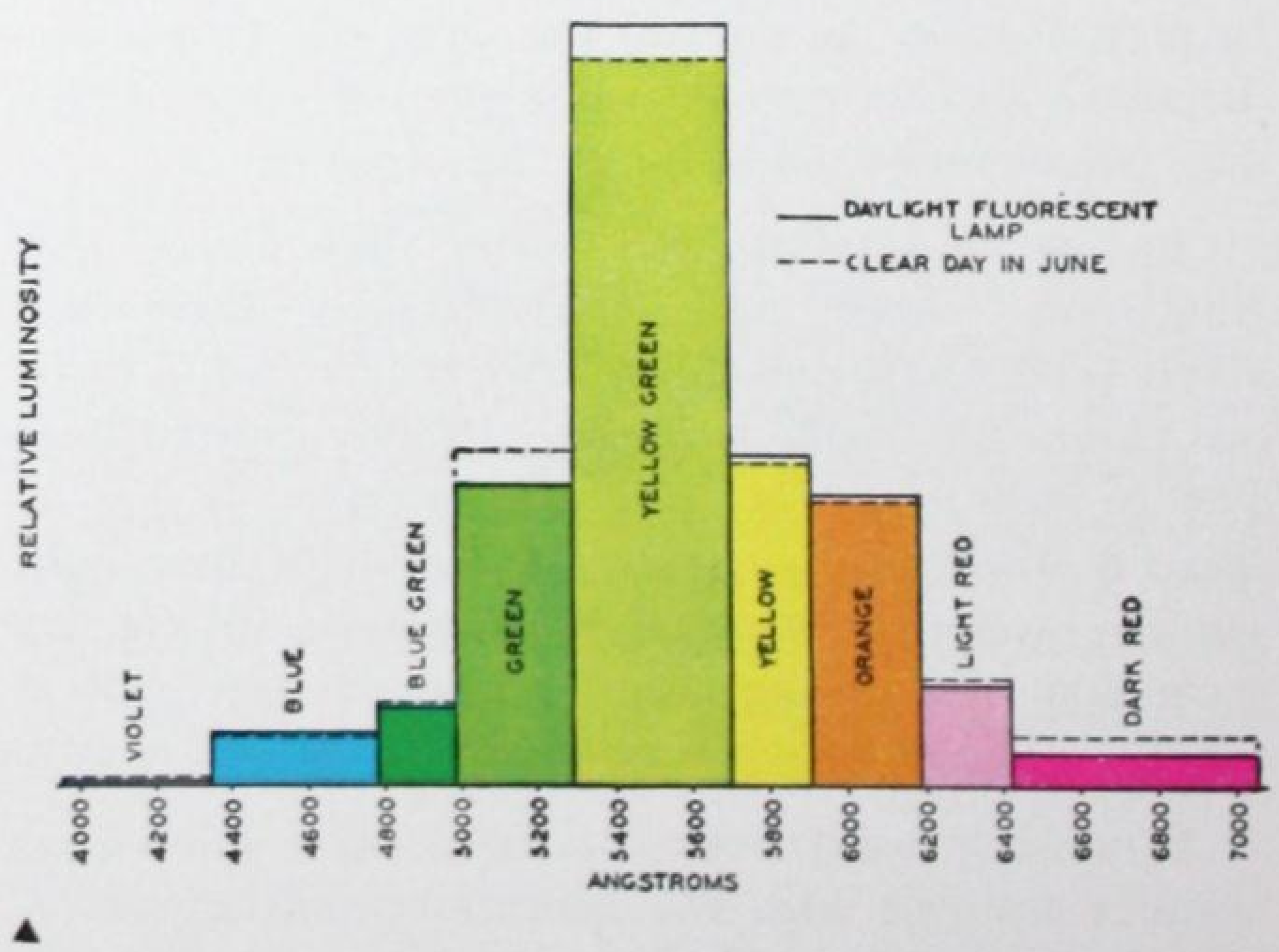
Fig. 30. Energy distribution of four white fluorescent lamps combining four rectangles with continuous curves. See also Fig. 31.

tinuous spectrum radiated by the fluorescent coating and a "line" spectrum produced by the mercury arc; the radiation from the arc represents the brighter bands and is almost entirely confined to four lines. If the arc energy is shown in a series of four rectangles, the combination of these with the continuous curve indicates somewhat more vividly the energy distribution of the lamp (Fig. 30).

Another method is to divide the spectrum into nine spectral bands and plot the values of relative energy in each; the area of each block is proportional to the total light of that color band. Comparison by this method of a 6500° K daylight fluorescent lamp and average June daylight is shown in Fig. 31.

Measurement of Ultraviolet Reflectance

The reflection characteristics of materials for energy in the erythemal and germicidal bands are similarly determined in the photometric laboratory. Such information is not only obtained for metals used for reflectors but also for paints for wall and ceiling finishes. The latter are of special importance in hospital ward rooms, treatment rooms, and in public rooms in which ultraviolet radiation may be of a harmful magnitude or direction through lack of control of these secondary surfaces.



▲

Fig. 31. Nine spectral bands indicate by their relative area the total relative enery in each color.

PART IV
FIELD MEASUREMENTS OF ILLUMINATION AND BRIGHTNESS

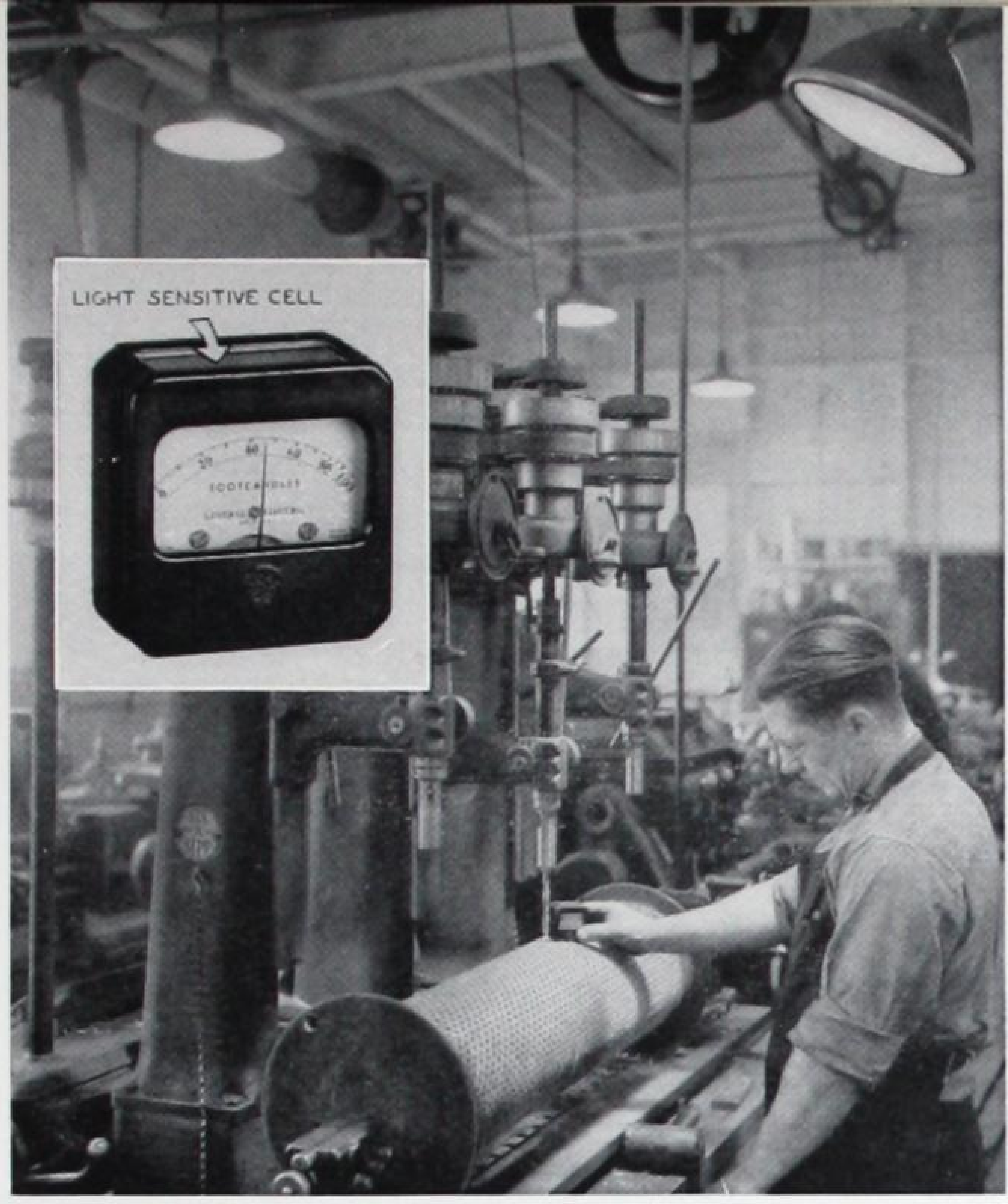


Fig. 33. Using the light meter in an industrial plant to measure illumination on a drill press.

A scientific approach to the appraisal of a lighting system requires skill in the selection and use of portable instruments. Readings taken with such instruments become the fundamental basis for a clear understanding of lighting effects and provide tangible data for guidance in analyzing lighting practices.

The Light Meter

The introduction of the light-sensitive cell in 1932 made possible the design of small, direct-reading instruments for field measurements of illumination and brightness. A typical example is the General Electric light meter, a pocket-sized photometer, weighing only seven ounces. It is approximately two inches square and one inch thick. As may be seen from the "exploded" view, Fig. 34, it contains a light-sensitive cell, which is a steel plate with a selenium coating, sensitive to light. The cell converts light energy into electrical energy. The copper front contact, rectangular in shape, is attached to the negative side of the microammeter. Current in milliamperes is generated when light strikes the cell, and is registered by the pointer. The pointer returns to the zero position when the cell is covered or when no light strikes it, being counter-balanced by the coiled spring as indicated. The scale is calibrated in footcandles, the light striking the cell being integrated over its surface.

The integrating or averaging power of the meter is easily demonstrated if one points a flashlight with a lens-end lamp at the cell, at a distance of approximately one-half inch (Fig. 35). Obviously only a part of the cell receives the light. The reading represents a "weighted" average of the illumination produced. This integrating characteristic of the cell allows the use of "multipliers" to increase the range of the

Fig. 34. Exploded view of light meter.

Fig. 35. The cell integrates the light energy which strikes it. The G-E exposure meter used in photography is an adaptation of this meter.

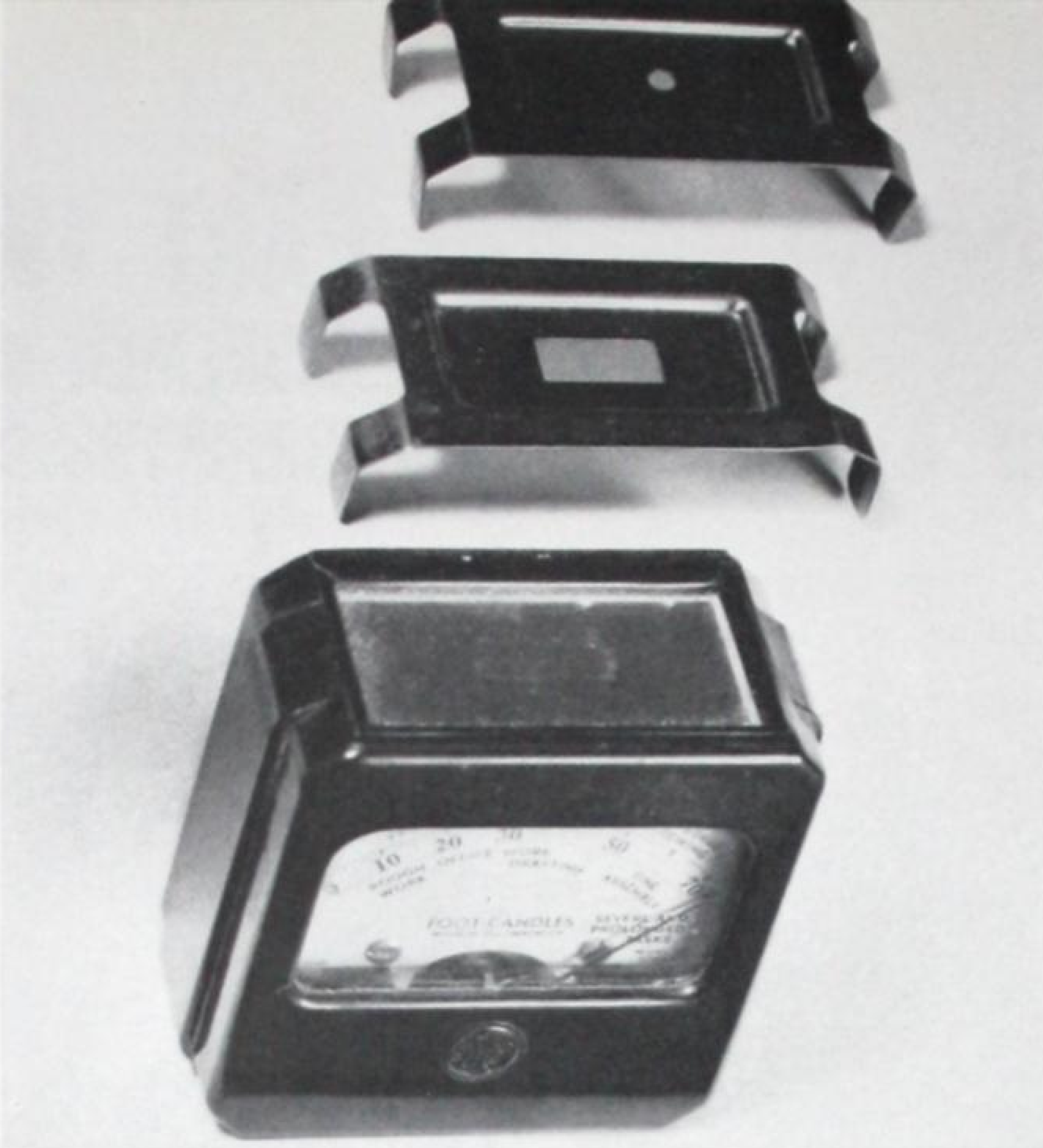


Fig. 36. The light meter and multipliers. For many years G-E light meters, introduced in 1934, had the 0-75 scale. Meters now have a 0-100 scale.

instrument. As shown in Fig. 36, multipliers of "10" and "100" are useful attachments. When placed on the cell, the readings are multiplied by 10 or 100, depending upon which is used. Thus the scale in the meter normally reading from 0 to 75 footcandles becomes 0 to 750 with the "times 10" multiplier, and 0 to 7500 with the "times 100" multiplier. Meters of this type with a 0-100 ft-c scale reading have a maximum range of 0 to 10,000 footcandles.

Light meters are calibrated under a color temperature* of 2700° K; this value was chosen because it is fairly representative of electric lighting in general, considering the effect of walls, etc., and the reading of the instrument applies directly for a fair range of color temperature. For light from common illuminants the readings are multiplied by a factor, as indicated in the following table:

TABLE 3 — APPROXIMATE MULTIPLYING FACTORS FOR G-E LIGHT METER SCALE READINGS

Source	Correction Factor
Filament lamps (2700° — 3400°K.)	1.0
High-intensity Mercury (Type E-H1)	1.0
Sun at Noon — 4800°K.	0.8
Average daylight — 6500°K.	0.7
Fluorescent Standard Warm White	1.1
Fluorescent De Luxe Warm White	1.0
Fluorescent Soft White	0.9
Fluorescent White	None
Fluorescent Standard Cool White	1.0
Fluorescent De Luxe Cool White	0.9
Fluorescent Daylight	0.9
Fluorescent Red	0.7
Fluorescent Pink	1.3
Fluorescent Gold	1.3
Fluorescent Blue	0.5
Fluorescent Green	1.5

Illumination measurements in interiors are commonly made on horizontal planes at the height of desks, benches, and other work areas where the surfaces viewed are flat or nearly so. Measurements on vertical planes are more important in stores where package goods are in wall displays, book stacks in libraries, and similar examples. Other angles are equally important in the analysis of illumination such as when books or papers are held at an angle of approximately 45°, such as in railway coaches. The illumination of oblique planes is also studied in numerous industrial processes, particularly in machine tools and in the inspection of finished materials.

Measuring Brightness with the Light Meter

As seen in Fig. 23, the light flux striking the cell of the meter comes from a wide angle but since the cell is covered by a glass plate, light at very wide angles reflects from the cover-glass and does not enter it. To measure the brightness of a diffusely reflecting sur-

Fig. 37. Measuring the brightness of a fluorescent lamp.

face, the cell of the meter is placed close to the surface and then drawn back two to four inches until a constant reading is obtained. The reading at this point is multiplied by 1.25 to correct for wide-angle losses. If the surface such as a painted wall is dull

* See definition, page 41.

finish or mat in character, it reflects light approximately equally in all directions, and a brightness reading in one direction is a true average brightness. To measure translucent surfaces such as the enclosing globe of Fig. 37, the cell is placed close to or touching the glass. A reading of 75 would indicate 94 footlamberts.

The Measurement of Reflectance

The approximate reflectance of mat materials can be measured with the light meter. It should be emphasized that reflection factors of materials depend upon the color of the light used. For example, a buff paint may have a reflectance of 55 per cent with filament lamps as the source, and 51 per cent with cool white fluorescent lighting. A surface painted a light blue, however, may have a reflectance of 55 per cent when lighted by filament lamps, and 57 per cent when illuminated by cool white fluorescent lamps. Light green paints have approximately equal reflectance for both colors of light, as do white, "off-white," aluminum paint, and the other shades of gray.

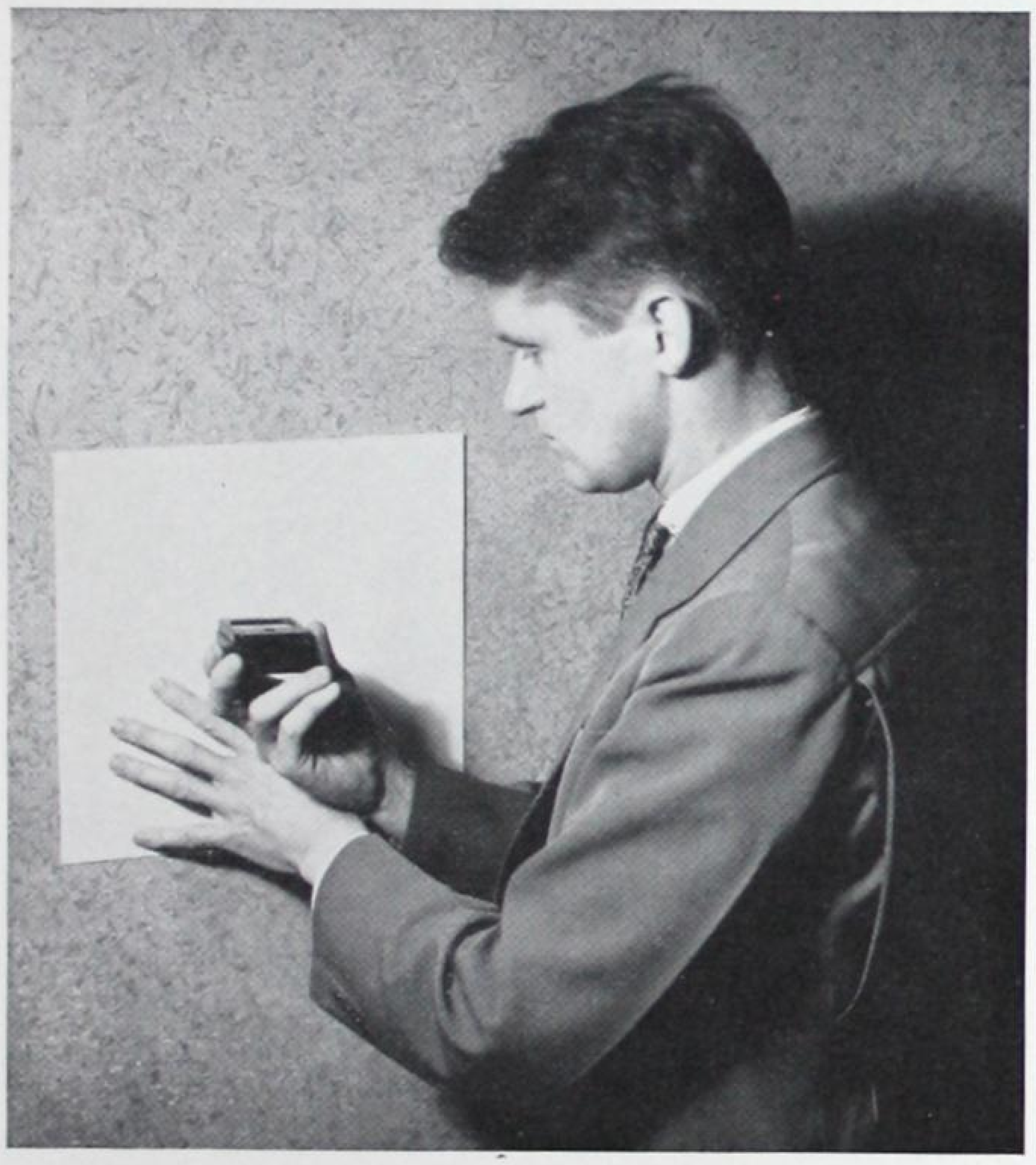


Fig. 38. Measuring reflection factor of a wall. By reading the brightness of a square of blotting paper, then removing it and reading the wall brightness, the reflectance of the wall may be determined by direct proportion.

There are two methods of measuring reflectance with the light meter, the first being somewhat more accurate. The first method makes use of a diffusing surface of which the reflectance is known. For this purpose, a piece of white blotting paper may be conveniently employed; the reflection factor of a typical sample* is about 75 per cent. About one square foot of the blotter is required, and this is placed against the surface such as the wall as shown in Fig. 38. A reading is taken with the meter held about three inches from it, with the cell pointed toward the paper. The blotter is then removed and another reading taken of the wall, with the meter held in the same position. The reflectance of the wall is equal to the wall reading divided by the blotter reading, and multiplied by the known reflectance of the blotter (75%). Thus if the wall reading were 5 footcandles, the blotter reading, 10 footcandles, the reflection factor of the wall would be 5/10 x 75 per cent or 37.5 per cent.

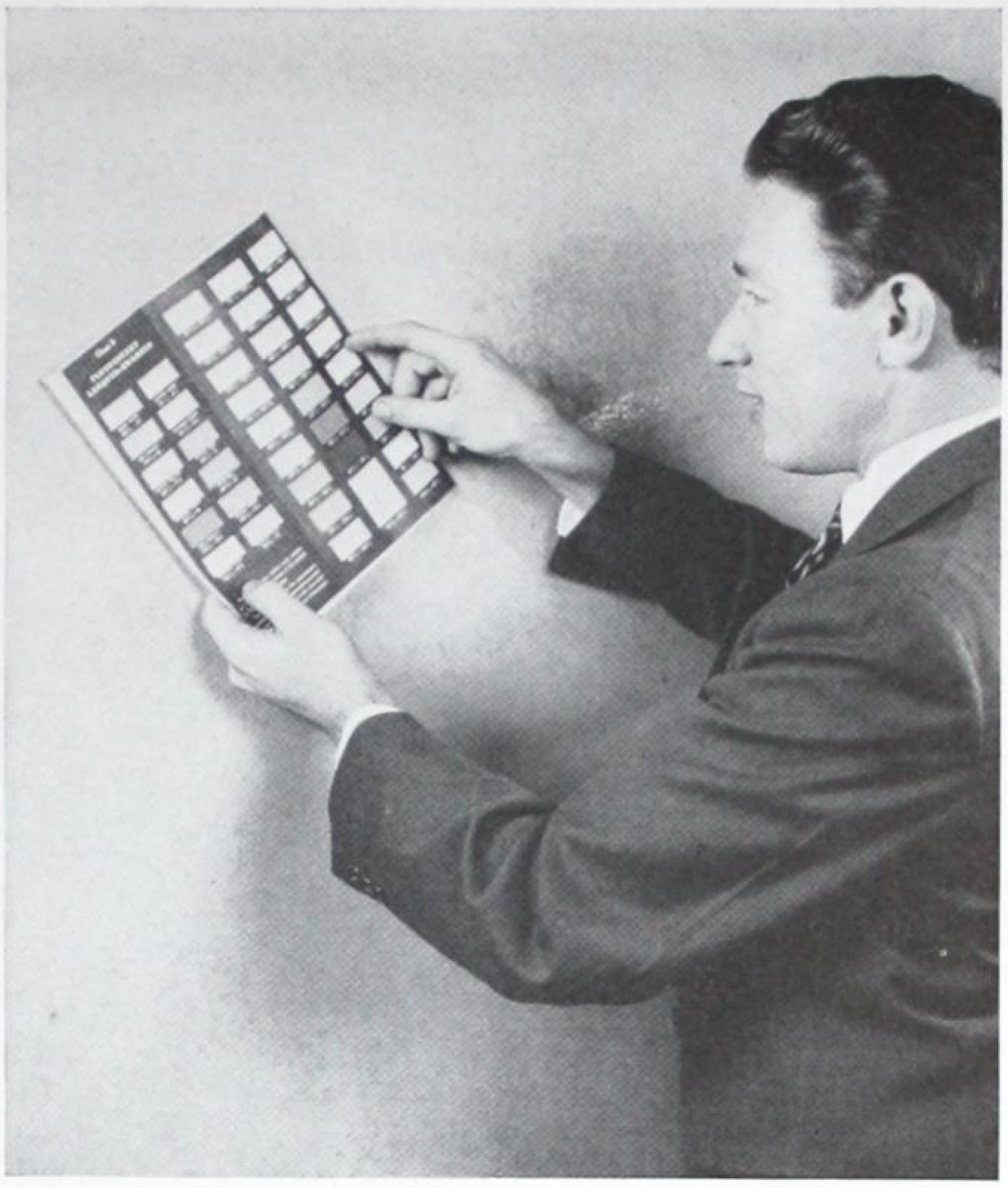


Fig. 39. Estimating wall reflection factor from paint samples. Such colored samples of wall coatings with known reflectances can be matched quite accurately to an "unknown" surface. The samples can be used for ceilings only if placed against them or in a position to receive the same illumination.

In the absence of a surface of known reflectance, another method gives very satisfactory results if certain precautions are taken. The light meter is first held against the wall and then drawn away from it,

* India Weave—70%; Arrow—73%; Albemarle Verigood—80%; Cavalier—77%; Halftone—78%.

(with the cell parallel to—pointed toward it) until the reading is constant, and the reading observed. Ordinarily the distance will be two to four inches. Then the meter is placed against the wall with the cell outward, and a second reading obtained. The ratio of the first reading to the second is the reflectance of the wall. Thus if the first reading is 6 and the second 12, the reflectance is 6/12 or 50 per cent.

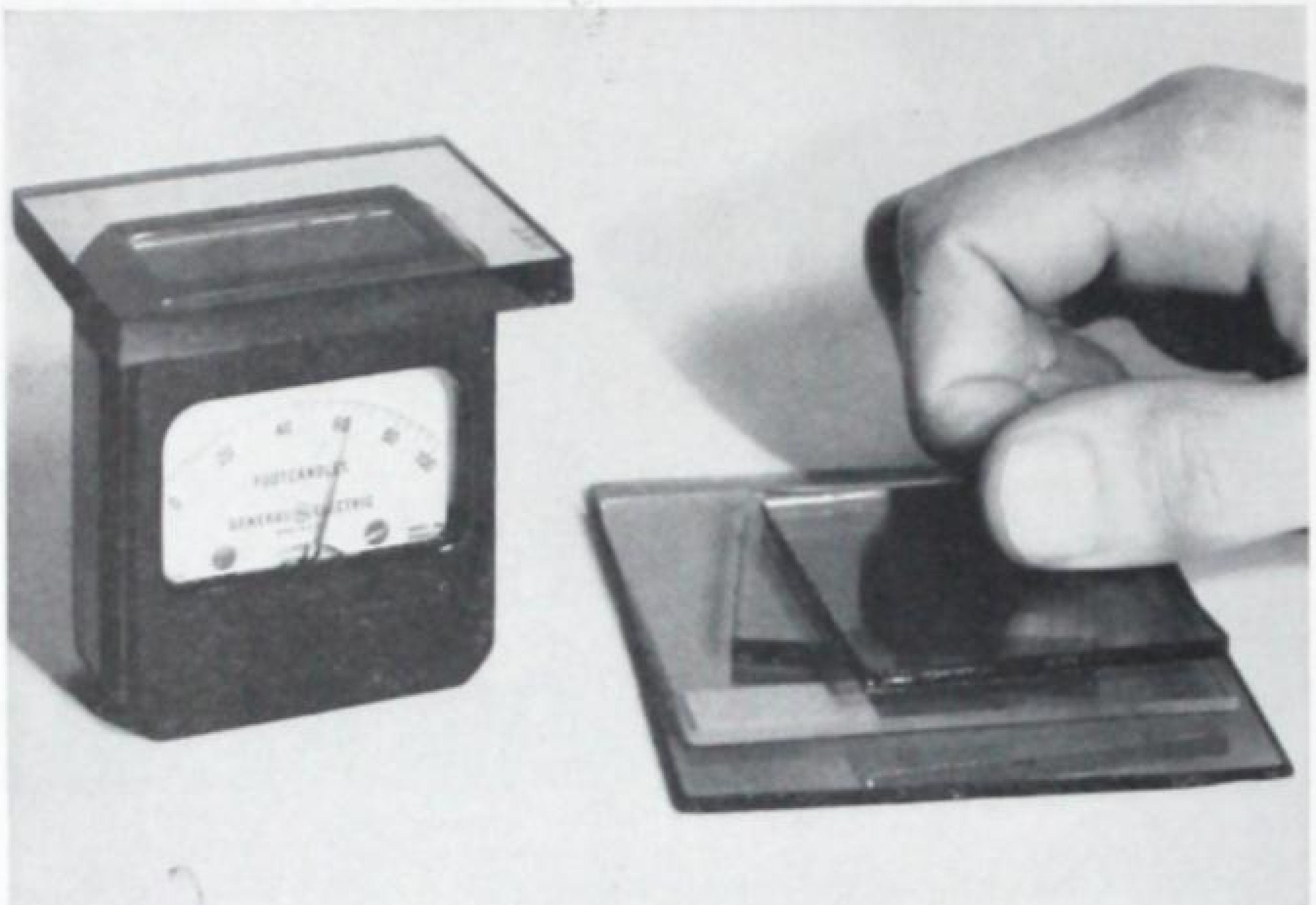


Fig. 40. Measuring transmission factor of glass. By placing the sample of material on the cell for one reading, then removing it for a second reading, the ratio of the two readings is the approximate transmittance.

In using these methods, it should be remembered that they are applicable principally to surfaces of non-specular or mat character. Care must also be taken that the sample is illuminated with fairly diffuse light and that conditions affecting the illumination for both measurements are constant. Thus when changing from one reading position to the second, it is necessary to make sure that the position of the person making the measurements does not change, nor that of other occupants of the room who may cast a shadow on the surface, or intercept light which would affect the reading. Fairly accurate readings of the diffuse reflection factor of a slightly glossy surface may be obtained if care is taken not to place the meter so that it intercepts the directly reflected beam.

A close appraisal of the reflection factors of walls may be obtained by comparing them with a table of samples, as shown in Fig. 39. The samples are held against the surface to be read, the surface being visually compared with the samples of the same or similar color. By interpolating between a sample just darker than the wall and one just lighter, the approximate value can be found. Thus if a buff-colored wall appeared to be between the two samples rated 55 per cent and 63 per cent, its reflection factor would be approximately 59 per cent.

Measuring Transmission Factors

Measurements of the approximate transmission factors of samples of glass or plastics may be made with the light meter by placing the sample to be measured over the cell for one reading, then removing the sample and taking a second reading (Fig. 40). The transmission factor is the ratio of the first reading to the second. In tests of this nature, it should be remembered that the transmission factor applies for light of the particular color used in the test, and may be quite different for light of dissimilar spectral character.

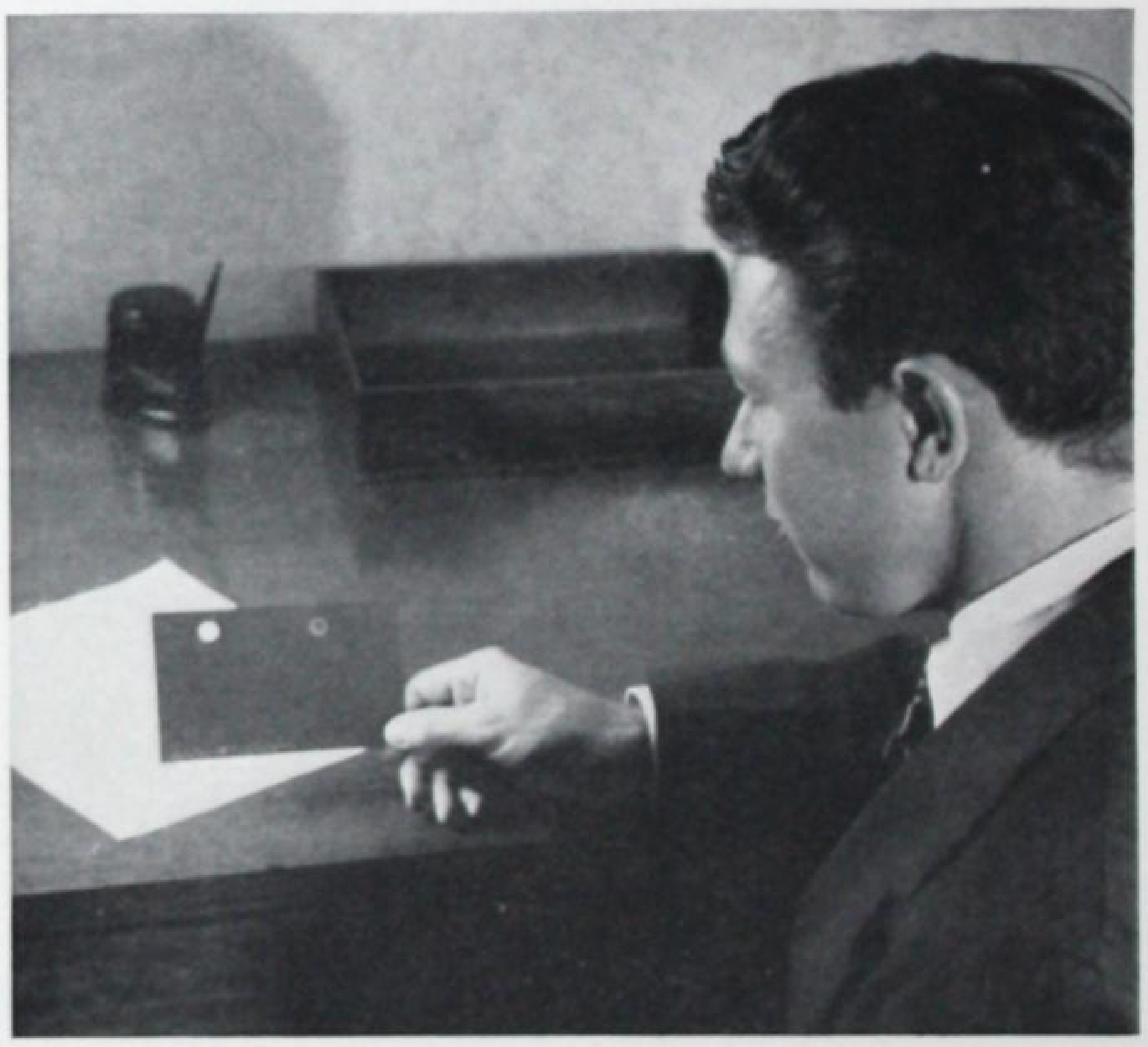


Fig. 41. Two sources of brightness can be compared with a 3 x 5 card with two ¼-inch holes, viewing one source in each. This is the principle of the comparison-type photometer.

Brightness Measurements

The eye is capable of detecting very small differences in the brightness of adjacent fields. This may be simply illustrated by punching two ¼-inch holes in a white 3 x 5-inch card and holding the card about two feet away from one eye, with the other closed. By means of this device, comparisons of such surfaces as the desk top vs. paper on the desk, the desk vs. the floor, walls vs. a luminaire, etc., can be made. This ability of the eye is utilized in actual measurements of brightness by making one of the two surfaces vari-

able in brightness and matching it to the other, which is the basic principle of the Macbeth illuminometer and the General Electric brightness meter; the latter is shown in Fig. 42.

Fig. 42. The General Electric brightness meter has a range of 2/1000 footlamberts to 50,000 footlamberts.

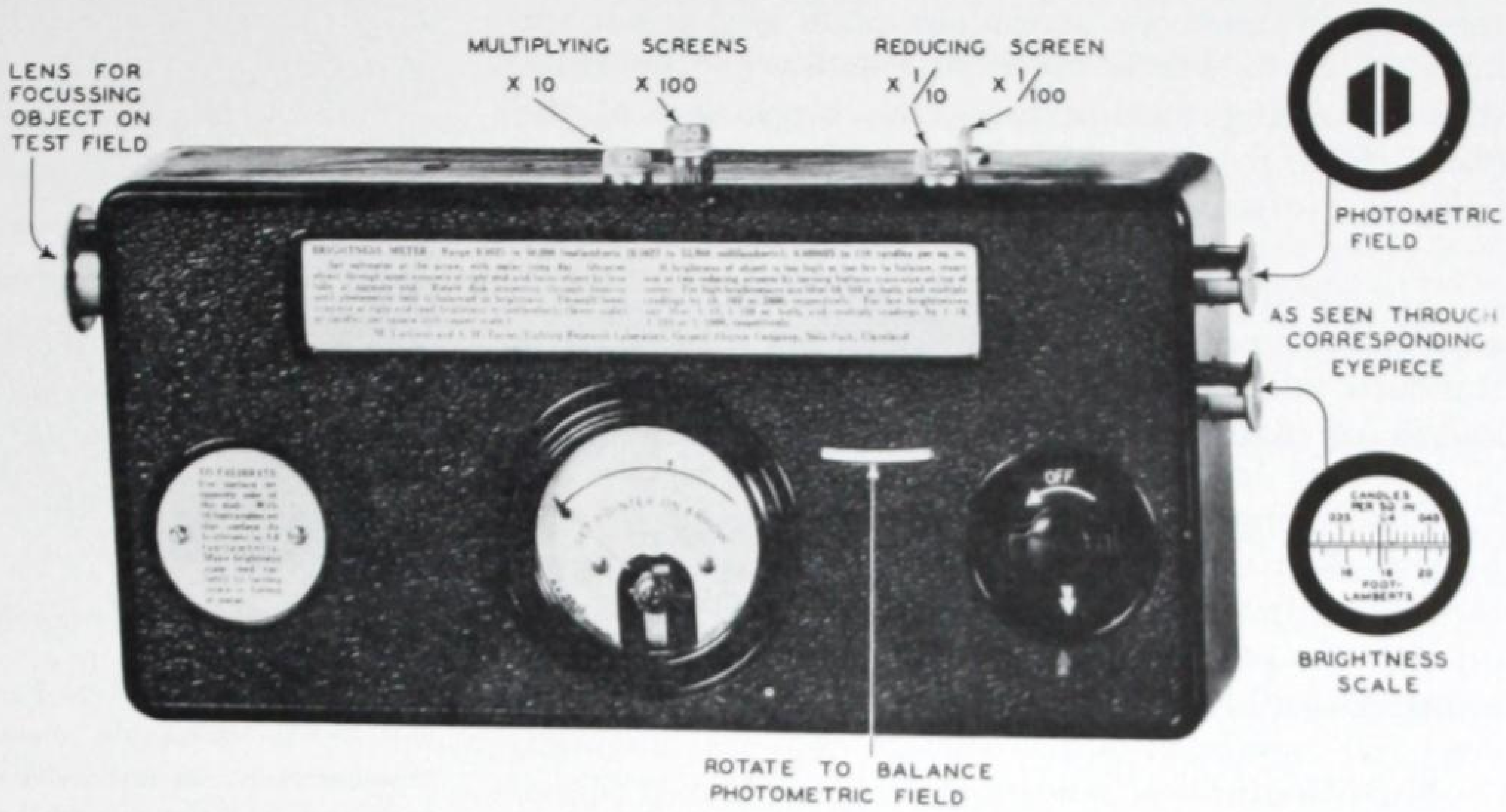


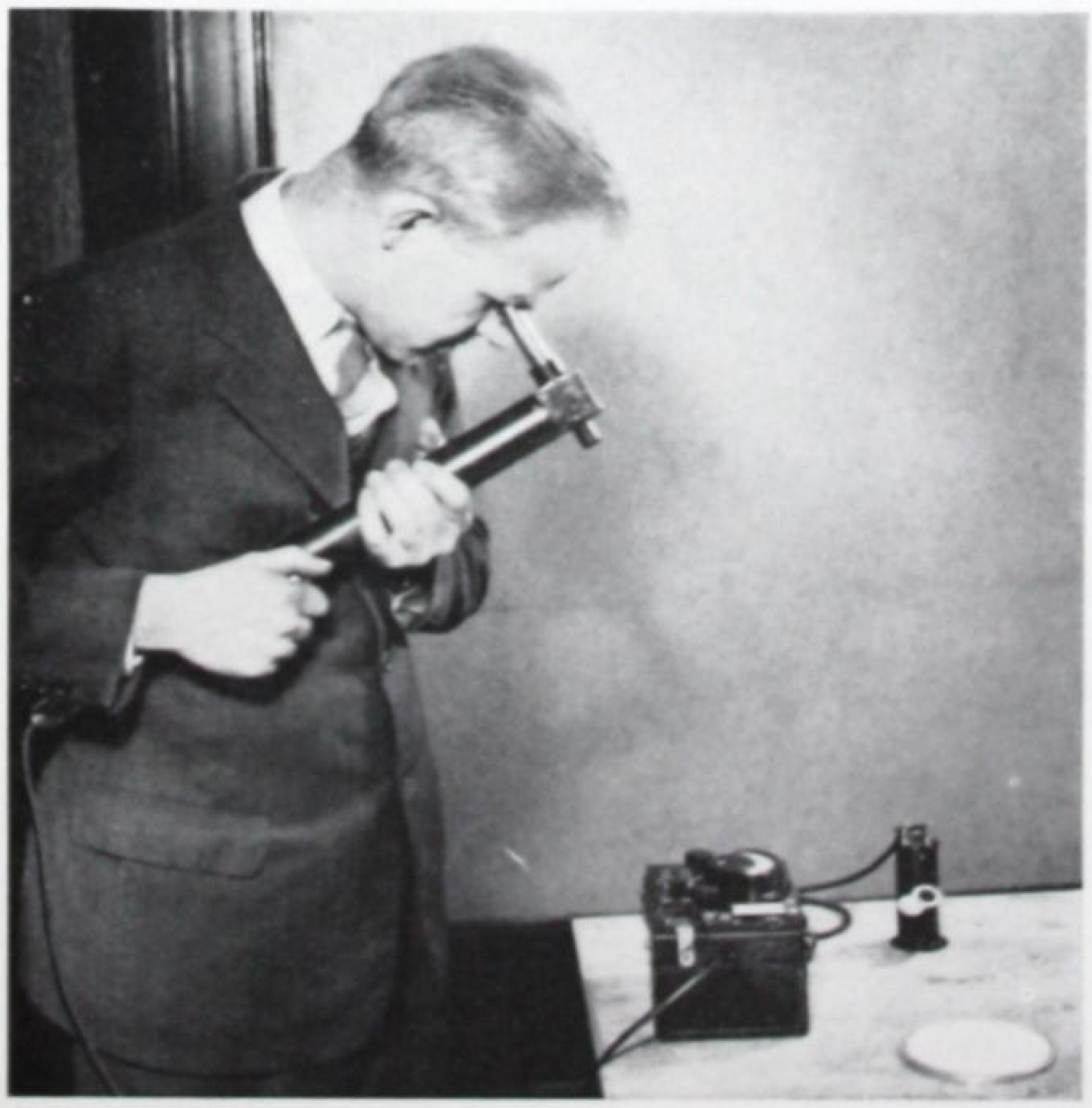
Fig. 43. Using the brightness meter to measure the brightness of a luminous wall.

▼

In the General Electric brightness meter, the brightness of the comparison field is varied by a photographic film gradient; the lamp is stationary and its light is transmitted through a white glass plate. In this instrument, the operator views the photometric field in the upper eyepiece shown at the right. The field contains two aluminized trapezoids which image the comparison field. The test field or surface to be measured, is brought into focus by the lens tube at the left end of the meter. By rotating the knurled wheel, the trapezoid field is adjusted to a brightness which matches the surrounding test field. When the balance is obtained, the operator reads the scale in the lower eyepiece, which shows brightness values both in candles per square inch and in footlamberts.

The adjusting buttons at the top of the meter are attached to multiplying screens which increase the range both upward and downward from the normal range of 2 to 50 footlamberts. The screens have multiplying factors of "x10" and "x100," which when used together become "x1000." Thus the upper range of the meter is 1000 times 50 or 50,000 footlamberts. The range may be extended downward by the reducing screens in the same manner, to .002 footlambert. The optical system which is used to focus on the object to be measured is of such magnification that it is possible to measure a surface one foot wide and several feet long at a distance of 500 feet.

Fig. 44. Macbeth illuminometer. For illumination readings a test plate is placed at the point in the plane in which the value is desired.



The Macbeth illuminometer has the comparison lamp on a rack-and-pinion gear (Fig. 44). The instrument consists of the illuminometer, the controller, and the reference standard. The illuminometer contains a Lummer-Brodhun cube. The operator peers through the telescope at the test plate and moves the knurled knob which moves the lamp in the tube, thus increasing or decreasing the brightness of the comparison field of the photometric screen until a balance is obtained.

The controller contains the battery for the lamps, a milliammeter, regulating rheostats for the reference standard and working standard, and a double-throw switch for changing the circuits from one to the other.

The reference standard contains a lamp so calibrated that when the specified current is passed through it, a definite illumination will be produced on the test plate on which it is placed. The illuminometer can in this way be checked at any time.

For illumination readings, the test plate is placed at the point where the illumination value is desired. When a balance is obtained on the photometric screen, the footcandles can be read from the scale on the square rod projecting from the bottom of the tube.

The scale is from 1 to 25 footcandles. Absorbing screens are provided to increase the range from .02 to 1200 footcandles. Readings of brightness are taken by substituting the source or surface to be measured for the test plate. Readings are multiplied by the known reflectance of the test plate to obtain footlamberts.

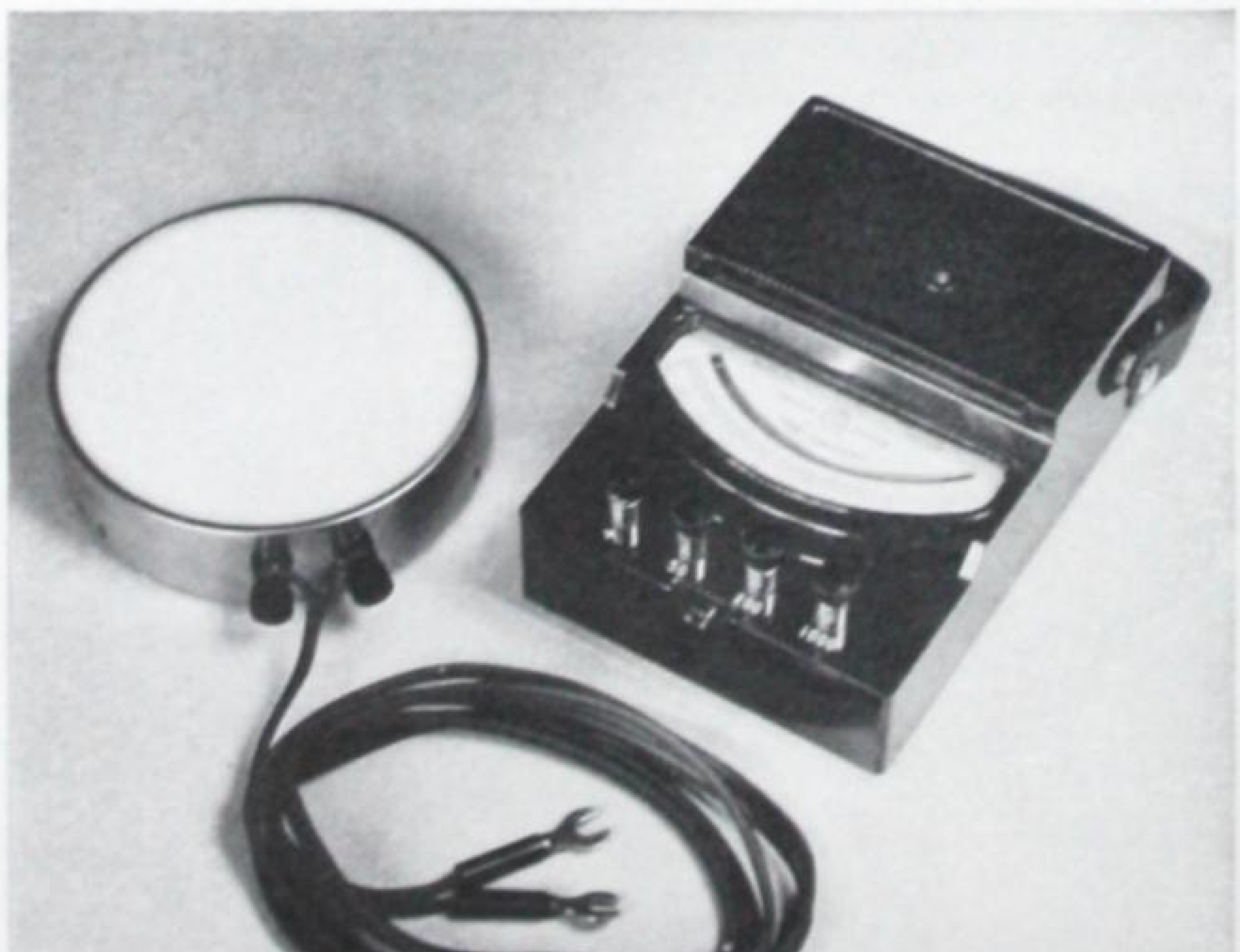


Fig. 45. The G-E Multi-Cell light meter has 50-, 200-, and 1000-fc scales. It contains a bank of color-corrected cells. The diffusing cover-plate traps wide-angle incident light.

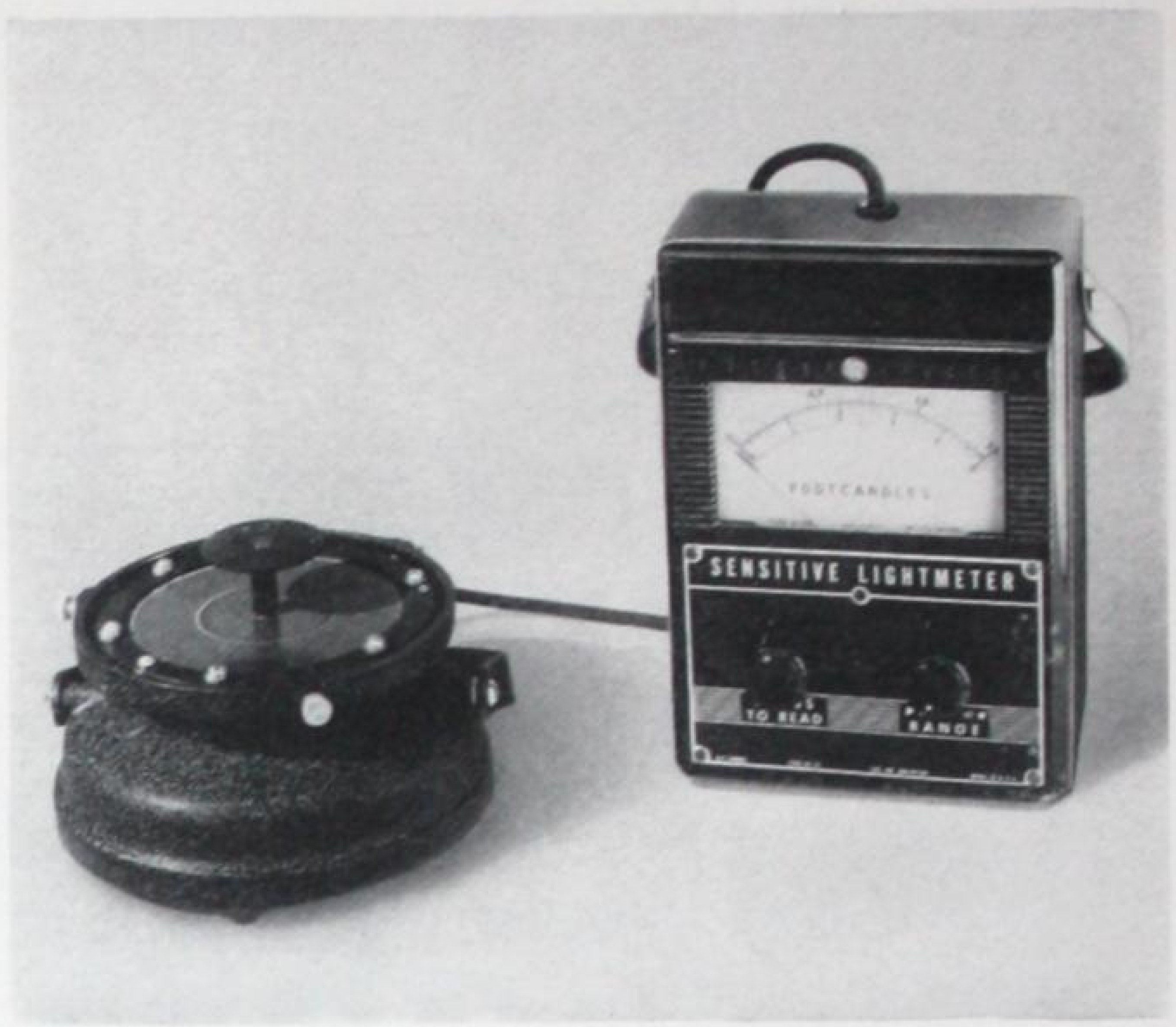


Fig. 46. The G-E Low-Range Precision light meter has 0-1.5 and 0-5.0 footcandle scales, primarily used in street lighting measurements. Its sensitivity is about 100 times that of the pocket-type and 50 times that of the meter of Fig. 45. The circular metal disk corrects for light at wide angles.

Measurements of candlepower are made by setting the test plate at a measured distance from the source and in a plane normal to it. Measurements are usually made in a dark room so that only the light from the source strikes the plate. The illumination on the plate is measured as previously described and this value multiplied by the square of the distance in feet is the candlepower of the source in that direction.

Two other portable instruments are shown in Figs. 45 and 46. The Multi-Cell light meter (Fig. 45) is designed for high accuracy of measurements in lighting surveys. The meter has scale ranges of 50, 200, and 1000 footcandles. It contains several color-corrected cells in parallel, under the diffusing plate. The plate gathers wide-angle incident light.

The Low-Range Precision light meter (Fig. 46) is chiefly used in street-lighting measurements. The full-scale is only 1.5 footcandles, with a 5.0 fc scale for higher values. The cell is mounted on a gimbal, which levels itself. The central part of the cell is shielded by a circular metal disk, which casts a shadow when the light is principally downward. When the light is from a wide angle, the disk shadow clears the cell and exposes the center portion, thus "correcting" the reading. The scale is lighted by a flashlight lamp, for ease in taking readings at very low illumination levels.

ILLUMINATION MEASUREMENTS*

The probability of error when making footcandle measurements in the field is relatively high even when the recorder is an experienced lighting man. In order to achieve an acceptable degree of accuracy in such field measurements, a standard method and form have been developed by the Committee on Lighting Practice of the Illuminating Engineering Society. The following comments on sources of error are brought to the attention of all persons involved in making illumination measurements, so that errors within the control of the recorder can be minimized and accuracy not expected that is beyond the limitations of the instruments used.

Changes in light output of lamps due to voltage variations, hours of burning, and dust and dirt depreciation make it desirable to report illumination measurements under the actual conditions found. Therefore it is extremely important to enter carefully the characteristics of the area on the report in order to evaluate properly the lighting system.

Selection of Instruments

There are two classes of portable light-measuring instruments used in illumination surveys of interiors: (1) those suitable for the approximate measurements involved in checking the ordinary commercial or industrial job, and (2) those suitable for the exact measurements required for comparing installations, calculating utilization coefficients, and similar applications where as high a degree of accuracy as possible is required:

(1) Instruments suitable for approximate measurements are of the photocell types such as light meters and illumination meters. They utilize a light-sensitive plate and a microammeter calibrated to read directly in footcandles. Inherent errors arise from the following causes:

A. *Eye Sensitivity Curve*—Uncorrected photocells do not respond to light radiation of various wavelengths in the same manner as the human eye. Consequently, they should be calibrated for the particular light-source to be measured, or the error known for the source supplying the illumination. This error, for light-sources commonly used in interiors, can vary from 5 per cent to 25 per cent, so its effect is important. Some cell-type instruments are equipped with filters, which give the cell the approximate response of the eye, thus removing this source of error.

B. *Angle of Incidence (Cosine Law)*—Light which strikes the face of the cell at angles other than the perpendicular is in part reflected from the cover glass, reflected from the cell surface, and obstructed by the rim of the cell case. The combined error is of the order of 25 per cent. This can be expected when measuring illumination in large areas where the luminaire has a widespread light distribution, and in any area where light walls, floors, and ceilings contribute an appreciable amount of flux.

C. Cell-type instruments have no provision for field calibration other than a zero reading correction, so they should be frequently checked against a master instrument of known calibration or returned to a reliable laboratory at frequent intervals.

D. Temperature affects the cell output, but not in a constant or predictable manner. To be on the safe side the instrument should be at the air temperature of the space being investigated, and preferably within a range of 60° to 90° F.

E. Like the human eye, many photocells increase in sensitivity when kept in the dark for several hours. A normal reading can be obtained only after the cell has been exposed for a period from several minutes to several hours. The only way to determine the interval for a particular instrument is to start with a dark-adapted cell and under a constant level of illumination watch for the time when the readings remain constant. The cell should then be exposed to light for this period before measurements are taken.

F. The microammeter used in connection with photoelectric instruments is subject to certain inherent limitations, in common with other electrical instruments, in the form of scale errors which vary in amount with the quality of the instrument. If the instrument has more than one scale, these should be so employed that no reading is taken in the range from zero to ¼ of full scale.

(2) Instruments suitable for more precise measurements are the Macbeth illuminometer, the General Electric brightness meter[1], and the Multicell meters[2], color corrected with diffusing plates. These instruments closely duplicate the eye sensitivity curve and take account of the cosine law.

The Macbeth and similar instruments are visual comparison types. In the hands of skilled users, and properly conditioned, they are capable of accuracy to within ± 5 per cent. Illumination is measured by noting the brightness of a surface of known reflection factor called a test plate. This should be white and must have a thoroughly mat texture. The viewing angle should not be greater than 30° from the perpendicular.

Preparation of Light Sources

(1) *Seasoning Period*—With incandescent lamps, seasoning is almost instantaneous. With gaseous-arc sources, particularly the fluorescent type, such seasoning requires not less than 100 hours of operation before stabilization at rated initial output results. The published average excess during this period is approximately 10 per cent but field experience indicates that it may be higher in individual cases.

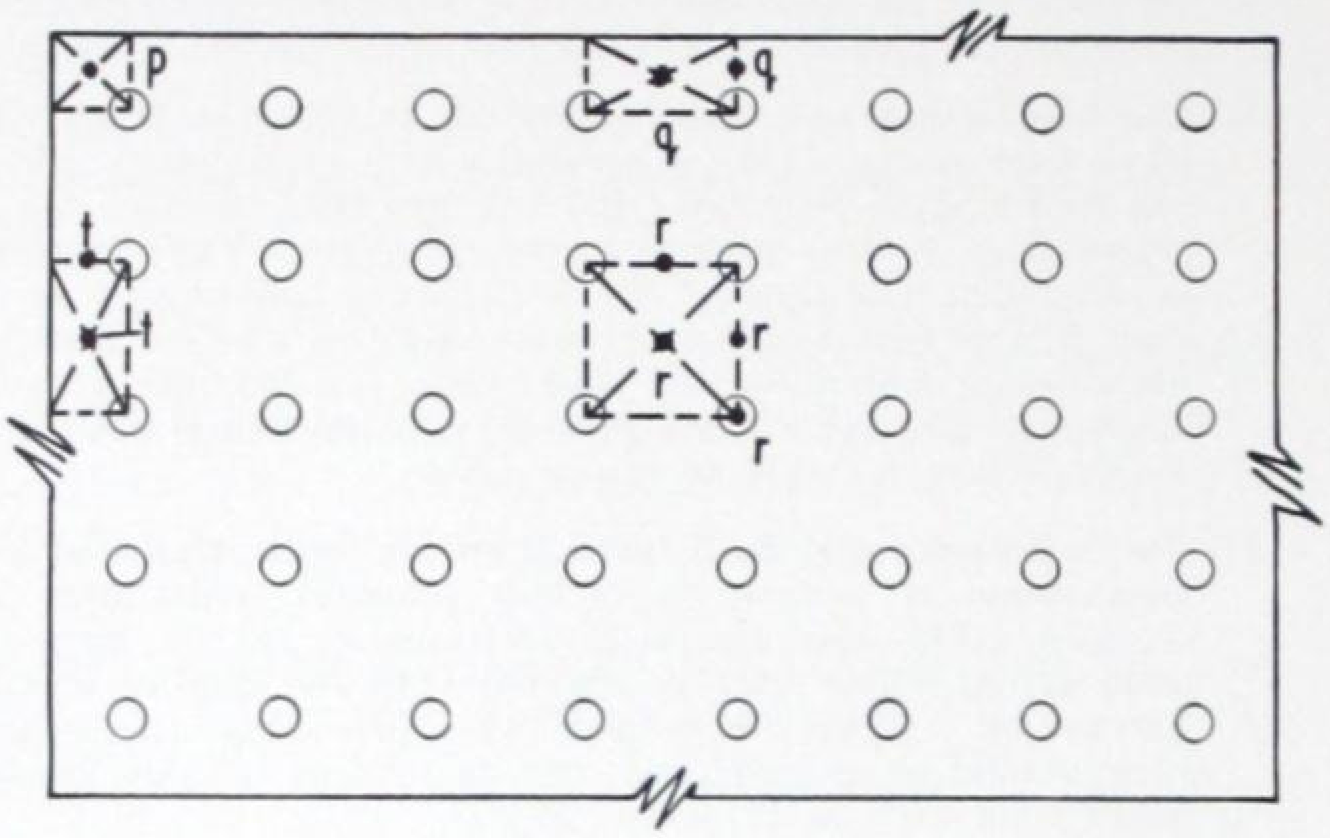
(2) *Temperature*—The light output of gaseous-arc sources, particularly fluorescent lamps, varies with ambient temperature, decreasing appreciably from design values if the temperature adjacent to the lamp rises above certain limits. These limits are often exceeded in operating luminaires resulting in a decrease in light output during the first half hour of operation. For this reason no readings should be taken of a gaseous source system until it has been in operation at least half an hour.

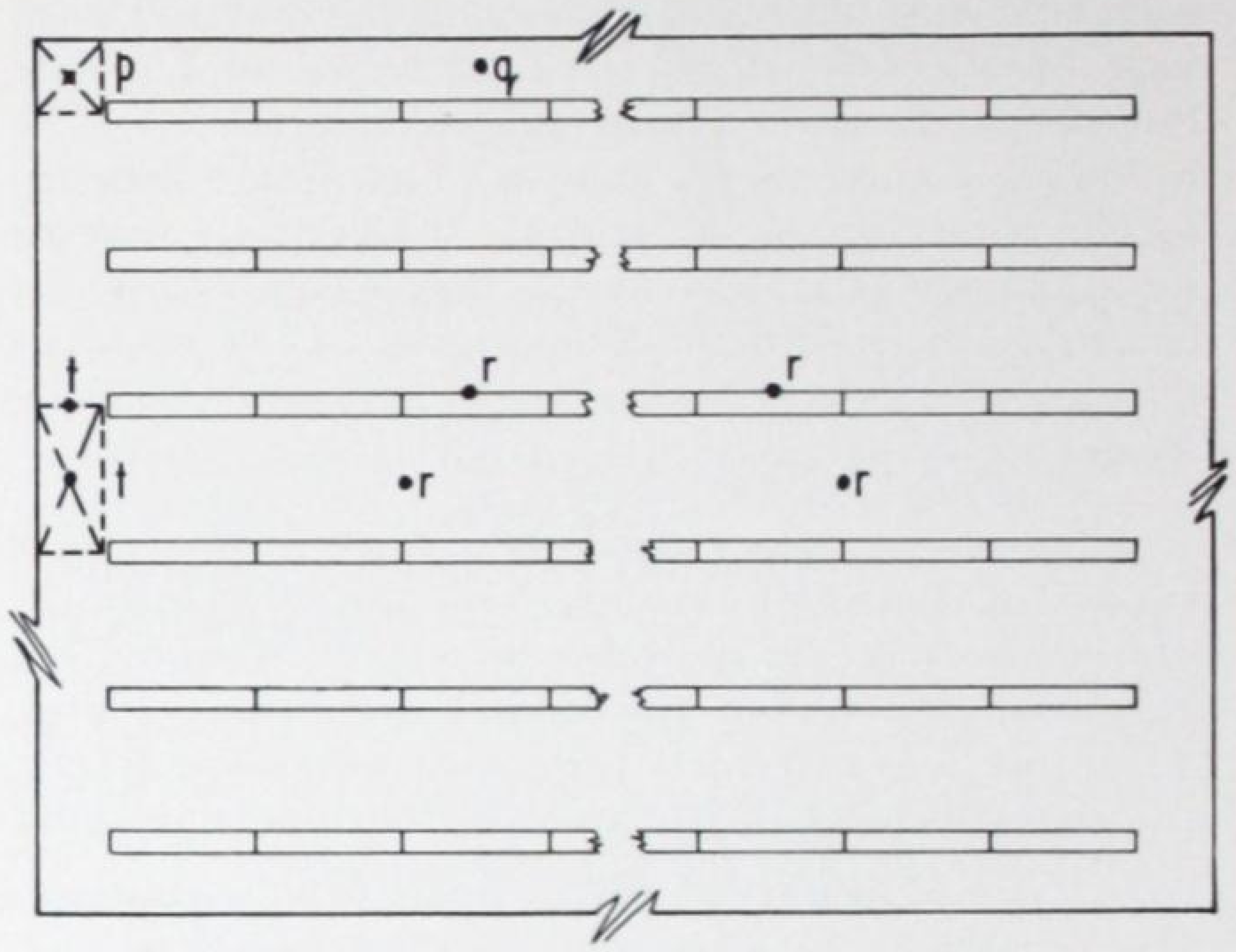
* From "Recommendations for a Standard Method for Measuring and Reporting Illumination from Artificial Sources in Building Interiors," published by the Illuminating Engineering Society.

[1] Illuminating Engineering, Vol. 37, No. 1, January, 1942, p. 19.
[2] Illuminating Engineering, Vol. 37, No. 2, February, 1942, p. 103.

INSTRUCTIONS FOR DETERMINING AVERAGE HORIZONTAL FOOTCANDLES

The purpose of the readings described below and the subsequent calculations is to arrive at the average horizontal footcandles for the entire area, usually at a height of 30 inches above the floor.





A—Regular Area with Symmetrically Spaced Individual Luminaires in Two or More Rows

Step 1. Select an inner bay of four units. Take four readings (r, r, r, r) as shown. Repeat in a centrally located bay and average the eight readings.

Step 2. Select a half bay at each side of the room. Take two readings (q, q) in each half bay midway between line of outside units and the wall, as shown, and average the four readings.

Step 3. Select a half bay at each end of the room. Take two readings (t, t) in each half bay midway between line of end units and the wall, average the four readings.

Step 4. In one corner of the room take one reading (p) as shown. Repeat in another corner and average the two readings.

$$\text{Av. Ill.} = \frac{\text{Ft-c in Step 1} \times (\text{No. of luminaires per row minus 1}) \times (\text{No. of rows minus 1}) + \text{ft-c in Step 2} \times (\text{No. of luminaires per row minus 1}) + \text{ft-c in Step 3} \times (\text{No. of rows minus 1}) + \text{ft-c in Step 4}}{\text{No. of luminaires}}$$

B—Regular Area with Single Row of Individual Luminaires

Step 1. Omit.

Step 2. Select two half bays on each side of the room and take two readings (q, q) in each half bay, as in A, Step 2. Average the eight readings.

Step 3. Omit.

Step 4. In one corner of the room take one reading (p) as in A, Step 4. Repeat in another corner and average the two readings.

$$\text{Av. Ill.} = \frac{\text{Ft-c in Step 2} \times (\text{No. of luminaires minus 1}) + \text{Step 4 average}}{\text{No. of luminaires}}$$

C—Regular Area with Single Luminaire

Step 1. Omit. Step 2. Omit Step 3. Omit.

Step 4. In each quadrant of the room take one reading (p) as in A, Step 4. Average the four readings.

Av. Ill. = Ft-c from Step 4.

D—Regular Area with Two or More Continuous Rows of Luminaires

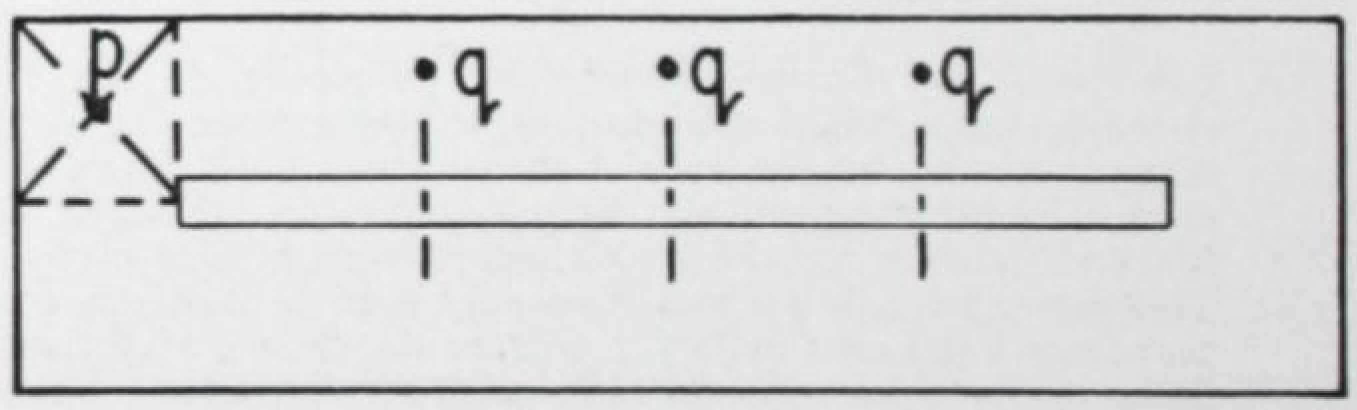
Step 1. Take four readings (r, r, r, r) near center of room as shown, and average the four readings.

Step 2. At each midside of room take one reading (q) midway between the outside row of units and the wall as shown. Average the two readings.

Step 3. At each end of room take two readings (t, t) one at end of a row midway between end of row and the wall, the other between rows and midway to wall as shown. Average the four readings.

Step 4. In one corner take one reading (p) as shown. Repeat in another corner and average the two readings.

$$\text{Av. Ill.} = \frac{\text{Ft-c in Step 1} \times \text{No. of luminaires per row} \times (\text{No. of rows minus 1}) + \text{ft-c in Step 2} \times \text{No. of luminaires per row} + \text{ft-c in Step 3} \times (\text{No. of rows minus 1}) + \text{ft-c in Step 4}}{\text{No. of rows} \times (\text{No. of luminaires per row} + 1)}$$



E—Regular Area with One Continuous Row of Luminaires

Step 1. Omit.

Step 2. Divide the continuous row into four equal lengths. Opposite each of the three division points and midway between the row of units and the wall, take a reading (q). Repeat on the opposite side and average the six readings.

Step 3. Omit.

Step 4. In one corner take one reading (p) as shown. Repeat in another corner and average the two readings.

$$\text{Av. Ill.} = \frac{\text{Ft-c (Step 2)} \times \text{No. luminaires/row} + \text{ft-c (Step 4)}}{\text{No. of luminaires plus 1}}$$

PART V

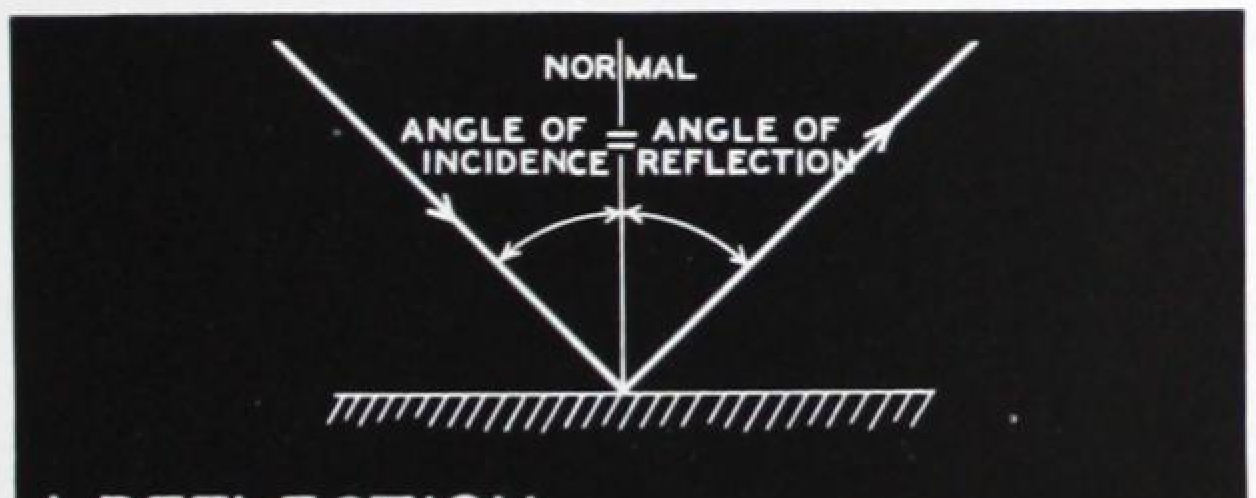
LIGHT CONTROL

In the early days of electric lighting, lamps were of relatively low light output and were commonly used without shielding of the direct rays from the eyes or redirecting the light into useful zones. In the years to follow, improvements in electric lamps were frequently made which brought about the development of larger light sources with higher light output. Such lamps were immediately put into use in an attempt to satisfy the demands for more light. At the same time, however, it became evident that lamps in the field of view must be shielded in order to reduce their brightness and minimize glare, and that reflectors and other light control media were very useful in this respect, as well as providing a better distribution of light.

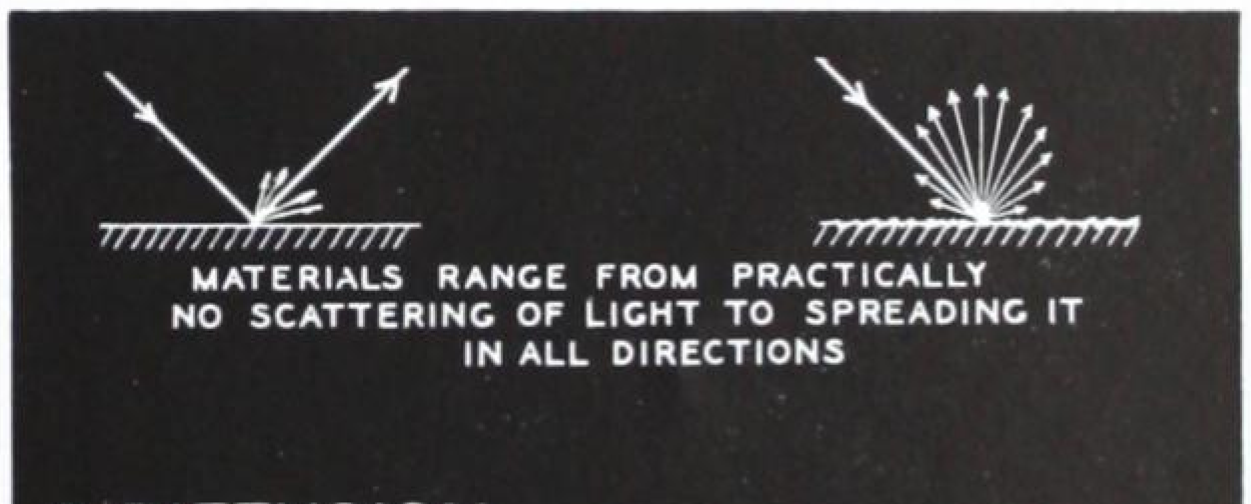
The usual means for controlling light are by:

1. REFLECTION
2. DIFFUSION
3. TRANSMISSION
4. ABSORPTION
5. REFRACTION
6. POLARIZATION

All of these methods are physical phenomena common in Nature and are everyday occurrences. The reflection of the sun on ice, water, and polished stones, are simple examples of the first. It should be borne in mind that most materials used in lighting systems have a combination of two or more of these phenomena; they are closely interrelated.

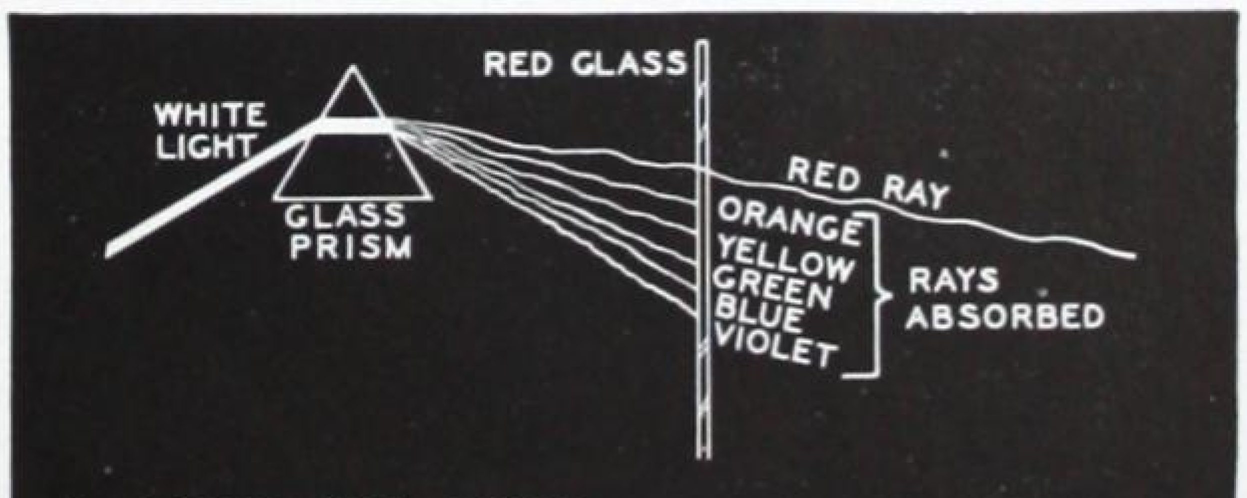


1. REFLECTION

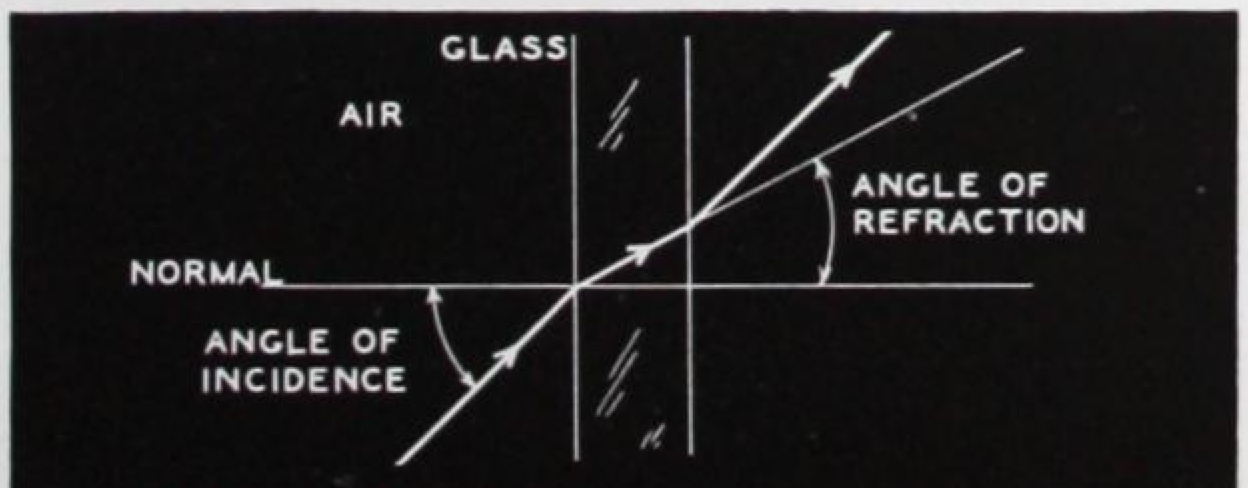


2. DIFFUSION

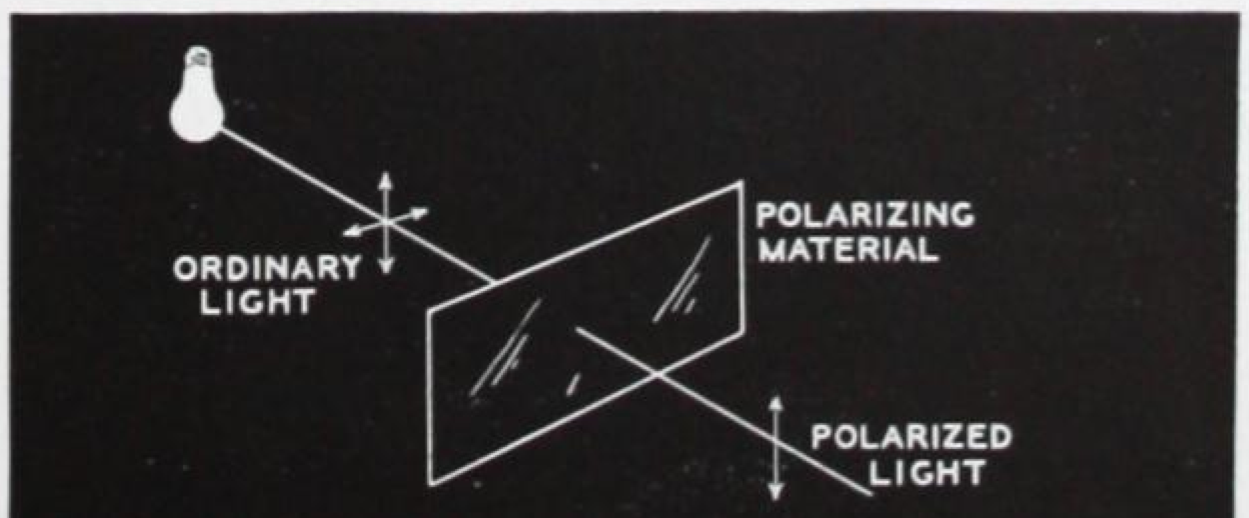
3. TRANSMISSION



4. ABSORPTION



5. REFRACTION



6. POLARIZATION

Fig. 47. The basis of accurate reflector design using polished materials is the simple law of specular reflection — the angle of incidence equals the angle of reflection. With curved reflectors the incident ray and the desired direction of the reflected ray must make equal angles with the normal at the point of incidence. Diffuse materials (upper half of the reflector shown at the right) destroy accurate light control.

When a beam of light strikes a first-surface flat mirror such as polished silver, *the angle of reflection is equal to the angle of incidence*. This is called the law of regular reflection. The diagram of Fig. 47 shows this relationship of the incident ray (left) and the reflected ray (right), both angles being measured from a line perpendicular to the surface, called the *normal*. In polished or specular materials, the image of a light source is sharply defined and the control of light rays is relatively accurately accomplished. It is this characteristic which permits the accurate control of light which is typical of searchlights, beacons, automobile spotlights, and similar devices (Fig. 49). Searchlights and spotlights employ highly concentrated sources such as electric arc lamps and closely-coiled filament lamps. The contour of polished metal reflectors and mirrored glass reflectors are designed so that the reflector surface at each point redirects the beam in the desired direction. The light is usually not concentrated on one point at a fixed distance but the beam is one whose sides are essentially parallel. A minimum of spill-light is desirable for such service.

Reflection Factor

The ratio of the reflected light to the incident light, expressed in percentage, is termed the *reflection factor or reflectance*. Table 4 indicates 29 common materials many of which have been used in the manu-

Fig. 48. A piece of clear glass reflects approximately 10 per cent of the light. When held in the position shown, it acts as a mirror.

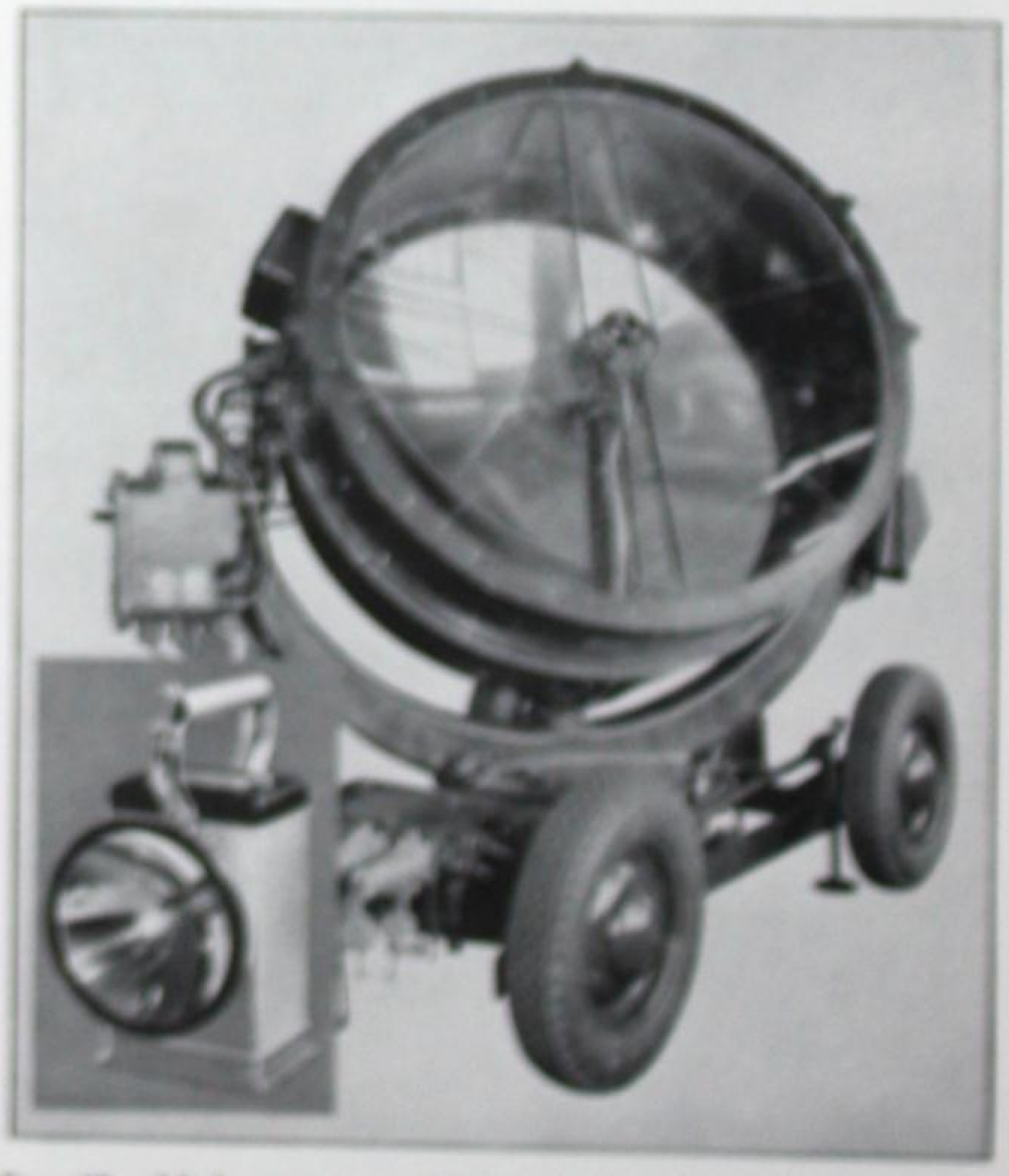
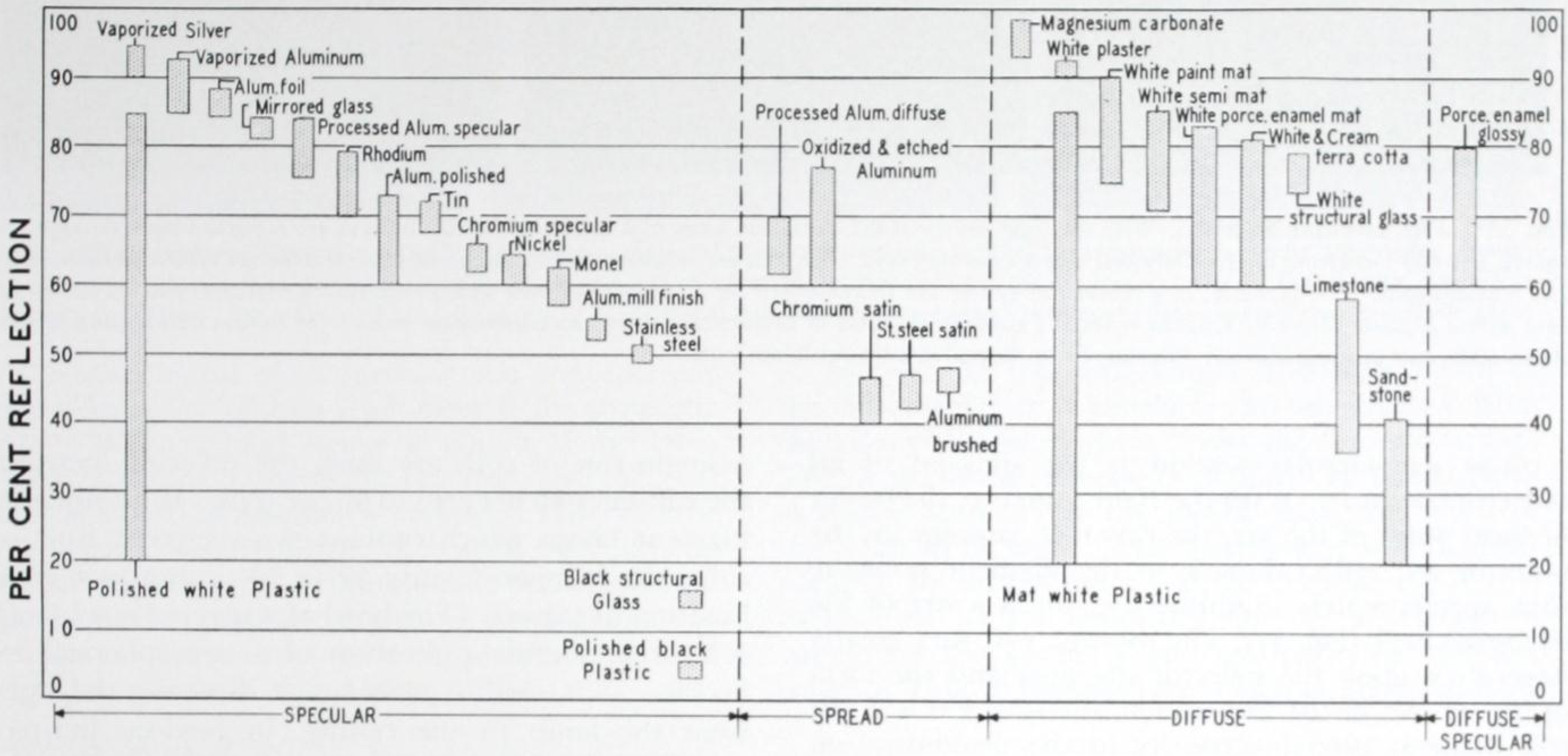
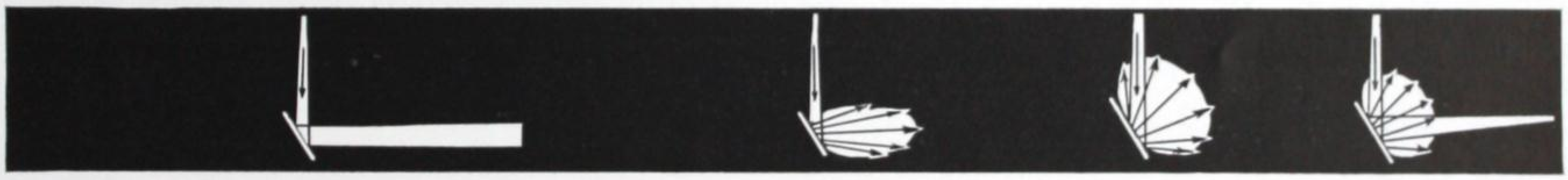


Fig. 49. High-power searchlights with mirrored glass reflectors and electric hand-lanterns are typical examples of regular reflection.

facture of reflectors for lighting devices and lighting elements in which the material is used for housings or other parts. Because the light reflecting characteristics are quite different, they are further classified as specular, spread, diffuse and diffuse-specular. The definition for each is included in the Glossary, page 84. It will be noted that the per cent reflection of these samples varies over a wide range. The material of highest reflectance is magnesium carbonate, a white, chalky material produced by burning magnesium.

TABLE 4 REFLECTION CHARACTERISTICS OF MATERIALS





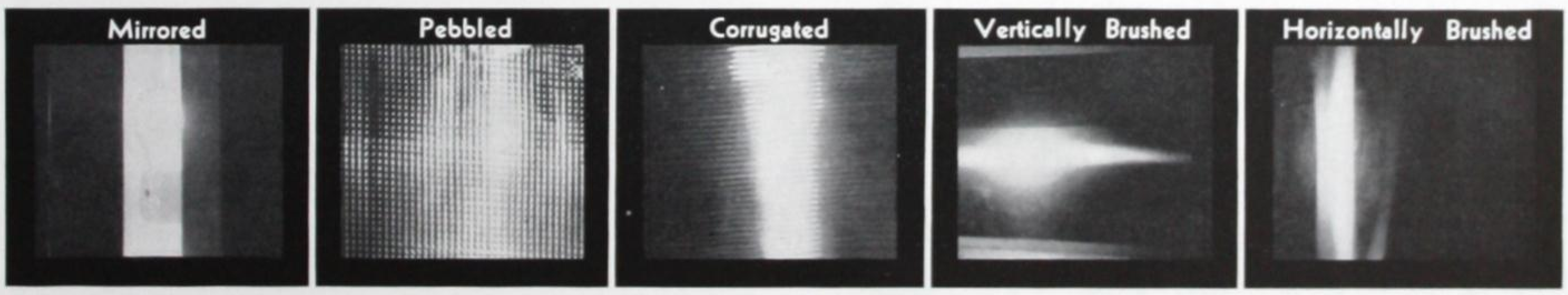


Fig. 50. **Plane specular or mirrored surfaces** appear dark except when the eye is in the path of the beam. Then the reflected image is only slightly less bright than the source. Notice the patch of highlights produced by the pebbled surface and the spreading of the light by brushed and corrugated surfaces.

The wide variety of reflecting materials makes their study an important part of the work of the designer of lighting equipment, as well as a matter of concern to the engineer, architect, and decorator in designing lighting effects. Any material which reflects light becomes a secondary source, and its illuminated appearance is often of primary importance, whether the objective is to obtain improved seeing conditions, to make a display prominent by a sparkling effect, or to create one of brilliant color contrast. The appearance of the material when lighted may be quite different from that which is anticipated, especially in the case of plane specular or mirrored surfaces. Some interesting examples of the appearance of mirrored, pebbled, corrugated, vertically brushed, and horizontally brushed surfaces are shown in Fig. 50. Actually, as shown in the illustration, the surfaces all appear dark except when the eye is in the path of the reflected beam. The reflected image may then be only slightly less bright than the source.

REFLECTOR CONTOURS—The Circular Section

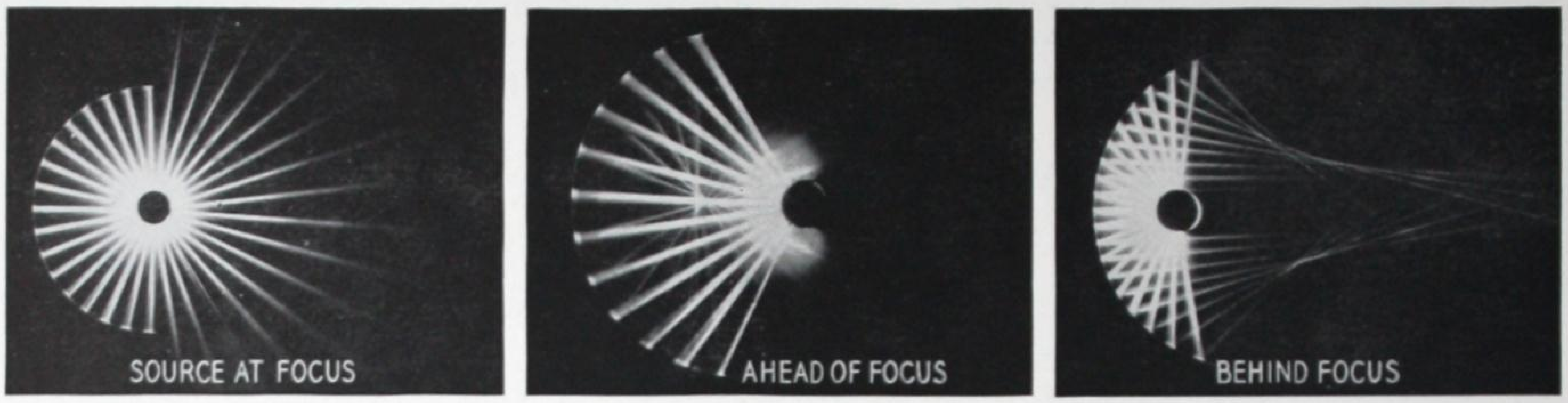


Fig. 51. **The Circular Section.** With the light source at the center or focus of a circular reflector the rays are reflected back through the source, thereby increasing the candlepower of the emerging rays. The increase will vary greatly depending on such factors as reflector efficiency and filament form. For example, in a projection system the increase will be 40 to 60 per cent with a monoplane filament, and 20 to 30 per cent with a biplane filament. Circular reflecting surfaces are used in projection systems to concentrate more light on the condensing lens, in downlights, and in some indirect reflectors (including silvered-bowl lamps), etc.

The semi-circular section is the simplest of all reflector contours. With the light source at the center or focal point of the arc, the rays that impinge on the reflector are reflected back to the filament position, thus approximately doubling the candlepower of the emerging rays (Fig. 51). The increase will vary greatly depending upon the reflector efficiency and the form of the source; in the illustration, the source is a single coil filament placed vertically in the demonstration projection lamp (Fig. 52). In conventional projection systems, when monoplane-filament lamps containing a single row of coils are used, the reflector increases the efficiency 40 per cent to 60 per cent. With biplane-filament lamps which contain two staggered rows of coils, the increase is only 20 to 30%, due to a combination of factors. The bowl of a silvered-bowl lamp is another useful application of a hemispherical reflector. It is used as a means of directing the light from the lamp to the ceiling, in modern indirect lighting systems used in offices and schools, and in home lighting applications (Fig. 52).

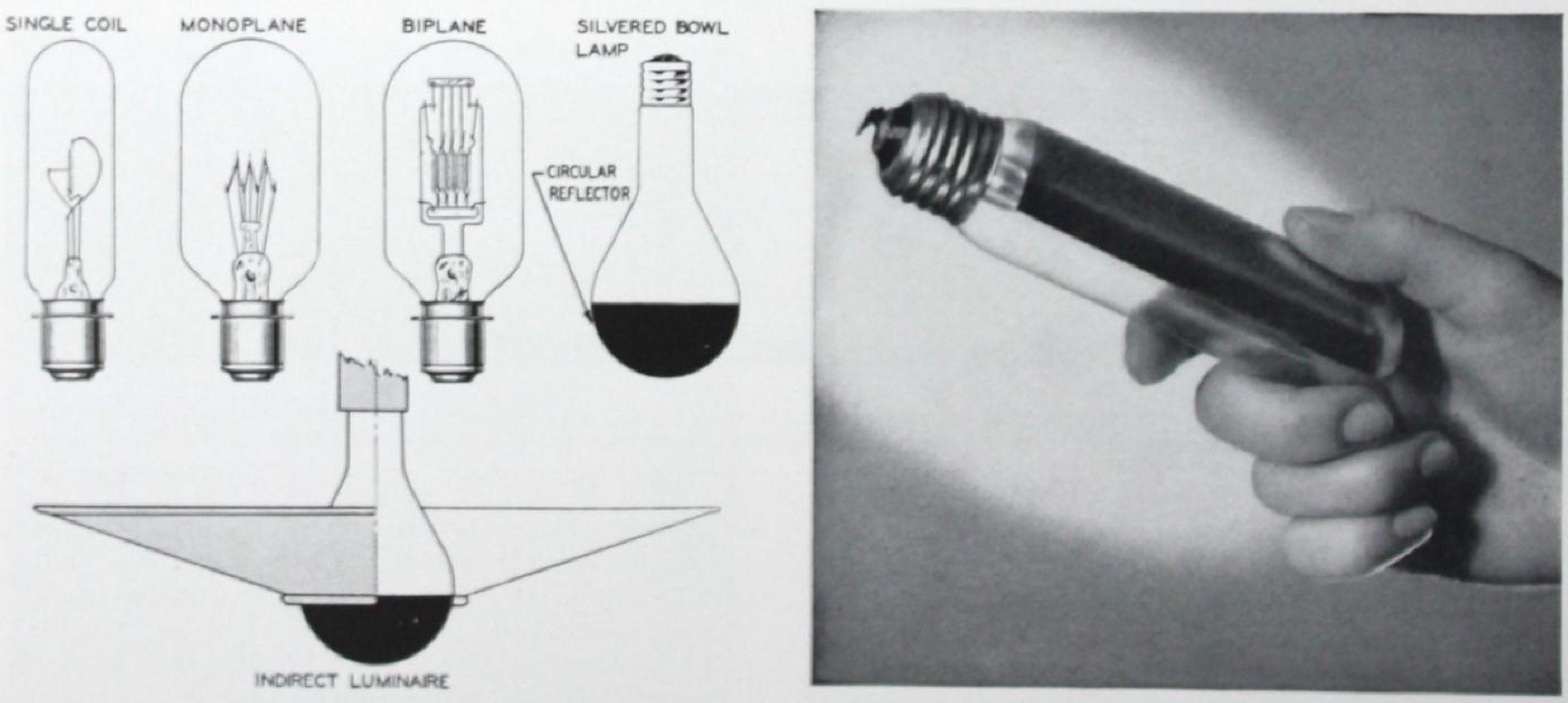


Fig. 52. The lamps used in projection systems have concentrated filaments. Shallow spherical mirrored reflectors are placed behind them. The silvered-bowl lamp is a simple example of a spherical reflector applied to the lamp bulb. A similar example is the show-case reflector lamp (right). The bulb is half-coated with aluminum on the inner surface; the reflector is cylindrical. The coiled-coil filament is placed off-center (behind focus).

REFLECTOR CONTOURS—The Parabolic Section

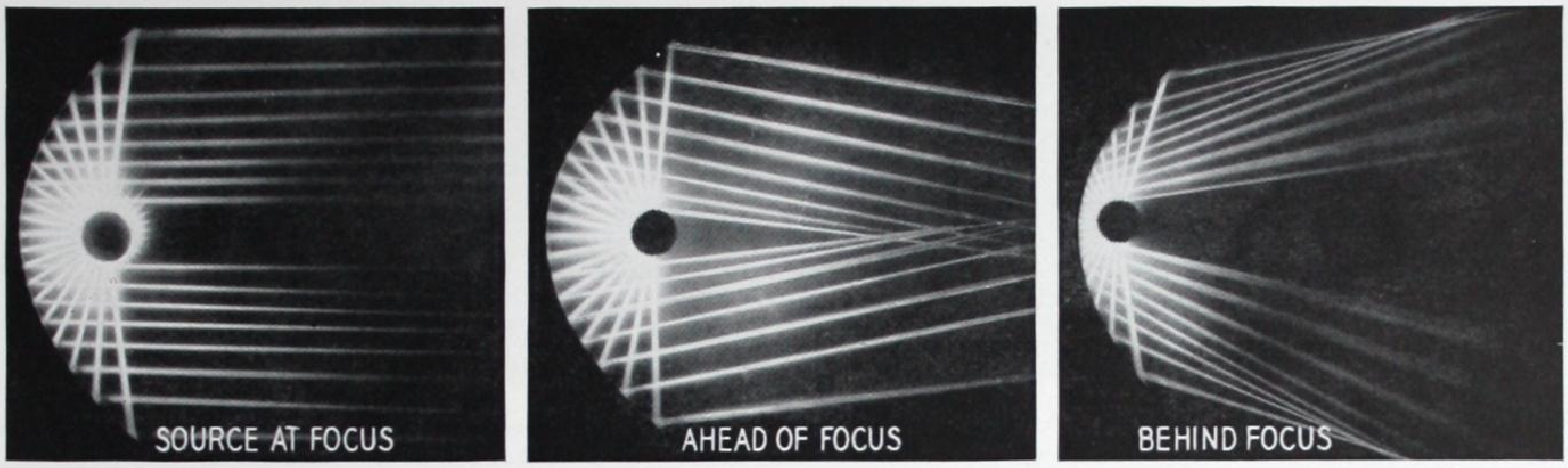
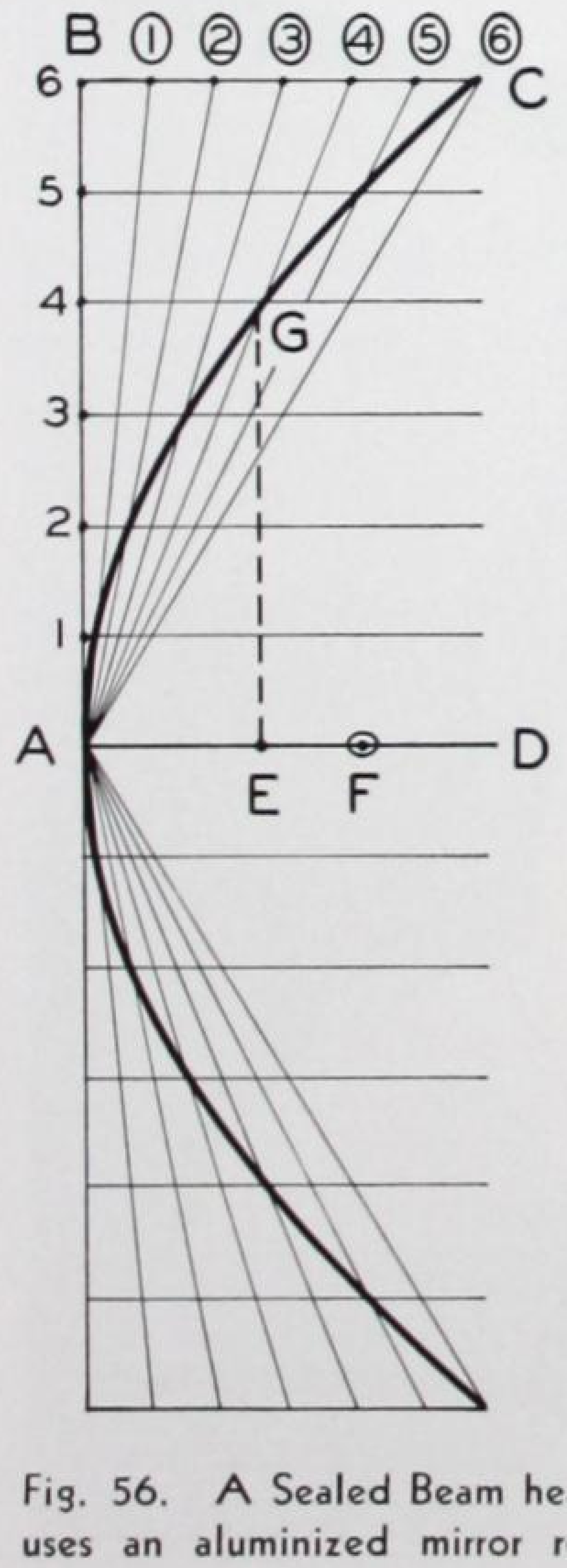


Fig. 53. **The Parabolic Section.** If the light source is at the focal point of a parabolic section, the reflected rays will be essentially parallel. (As pointed out above there will be some divergence because of source dimensions.) This contour is used in searchlights, spotlights, automobile headlights, etc. The center and right-hand illustrations show the loss in control that results from having the source off focus.

The most useful of all specular and semi-specular reflector forms in lighting equipment is the parabolic section. When a light source is placed at the focus or focal point of a parabolic reflector, the reflected rays of light will be essentially parallel. This reflector shape is used in searchlights; spotlights; and, in combination with a lens, in automobile headlights; in coves; and other luminaires where a concentrated distribution of light is required. A simple method of drawing a parabolic curve is as follows:

In practice, the approximate allowable width of the reflector mouth is known or can be estimated from the allowable space, which limits the dimension A-B. The depth of the reflector is similarly estimated, with clearance allowed for the socket, base, and bulb of the lamp to be used. The final design would incorporate a lip on the outer edge of the reflector if it is to be used with a mounting ring, or a beading to strengthen the assembly and maintain the reflector contour. Typical reflectors are shown in Fig. 55 and 56.



Assume a line A-B having a length equal to one-half the desirable diameter of the reflector and a line B-C equal to the desired depth. Then as shown at left, divide A-B into a convenient number of equal parts and divide B-C into the same *number* of parts. From the division points on A-B, draw horizontal lines. From the division points on B-C, draw lines to point A. The points of intersection between lines drawn from points numbered alike are points on the parabola.

To locate the focal point F on A-D, draw a vertical line at E, with A-E equal to one inch. Measure E-G. Then $A\text{-}F = \frac{(E\text{-}G)^2}{4}$, in inches. Any convenient linear unit such as centimeters or millimeters may be used instead of inches.

Fig. 54. A parabola is formed by a plane parallel to one side of a cone.

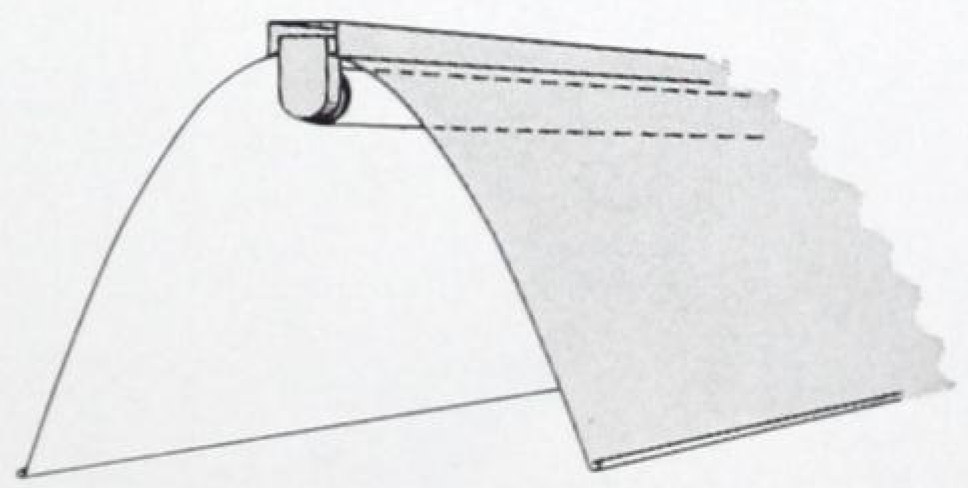


Fig. 55. Cut-away view of typical parabolic reflector.

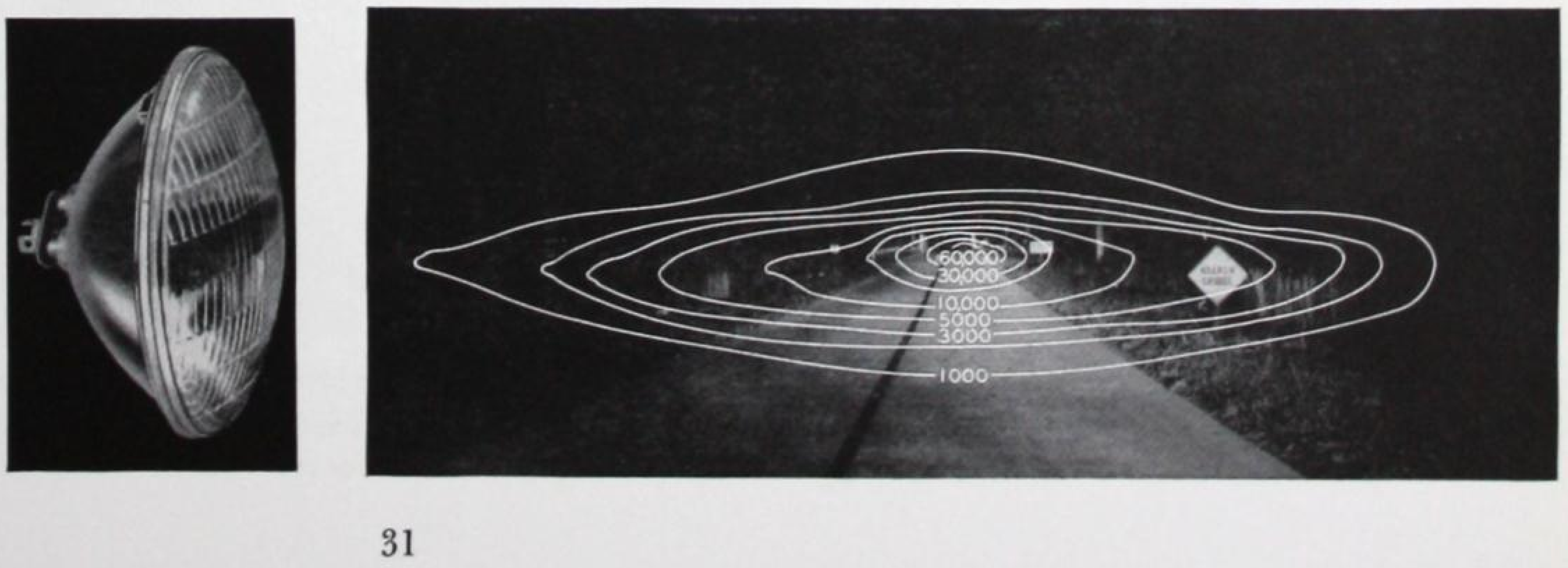


Fig. 56. A Sealed Beam headlamp uses an aluminized mirror reflector and prismatic lens-cover to secure an accurate beam pattern (left). Values of beam candlepower plotted on the road (right).

PLANE, PARABOLIC, AND CIRCULAR SECTIONS

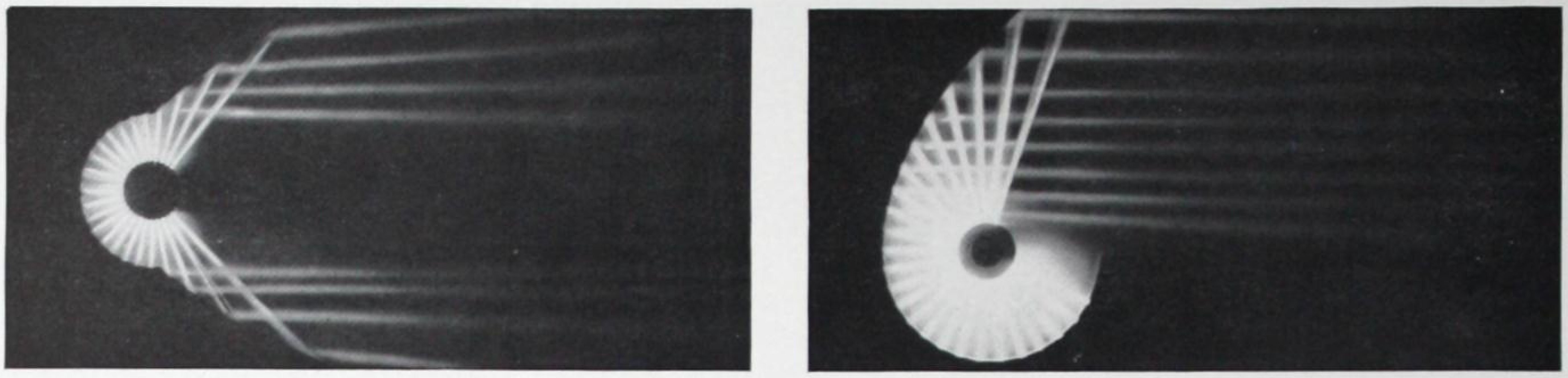


Fig. 57 — Circular-Parabolic Sections. A small reflector can be designed by combining the circular and parabolic sections. At the left, where the source is at the focus of both contours, the rays reflected through the source by the circular contour are directed into the parallel beam by the parabolic section. The "paracyl" (right) is used for illuminating vertical surfaces. In this case the circular section shields the source from view while concentrating more light on the parabolic section.

Combinations of plane, circular, and parabolic sections are useful in reflector design. In the left illustration of Fig. 57, the source is at the focal point of both reflectors. Rays reflected by the circular section go through the source, are then redirected into a parallel beam by the parabolic reflector. Plane and circular reflectors are combined in the bracket luminaire (Fig. 58). The "paracyl" (Fig. 57-right) is used for illuminating vertical surfaces in commercial interiors. A circular reflector is a part of the heat lamp of Fig. 64. Light and heat energy is focused at a distance of about one inch from the mouth of the unit.

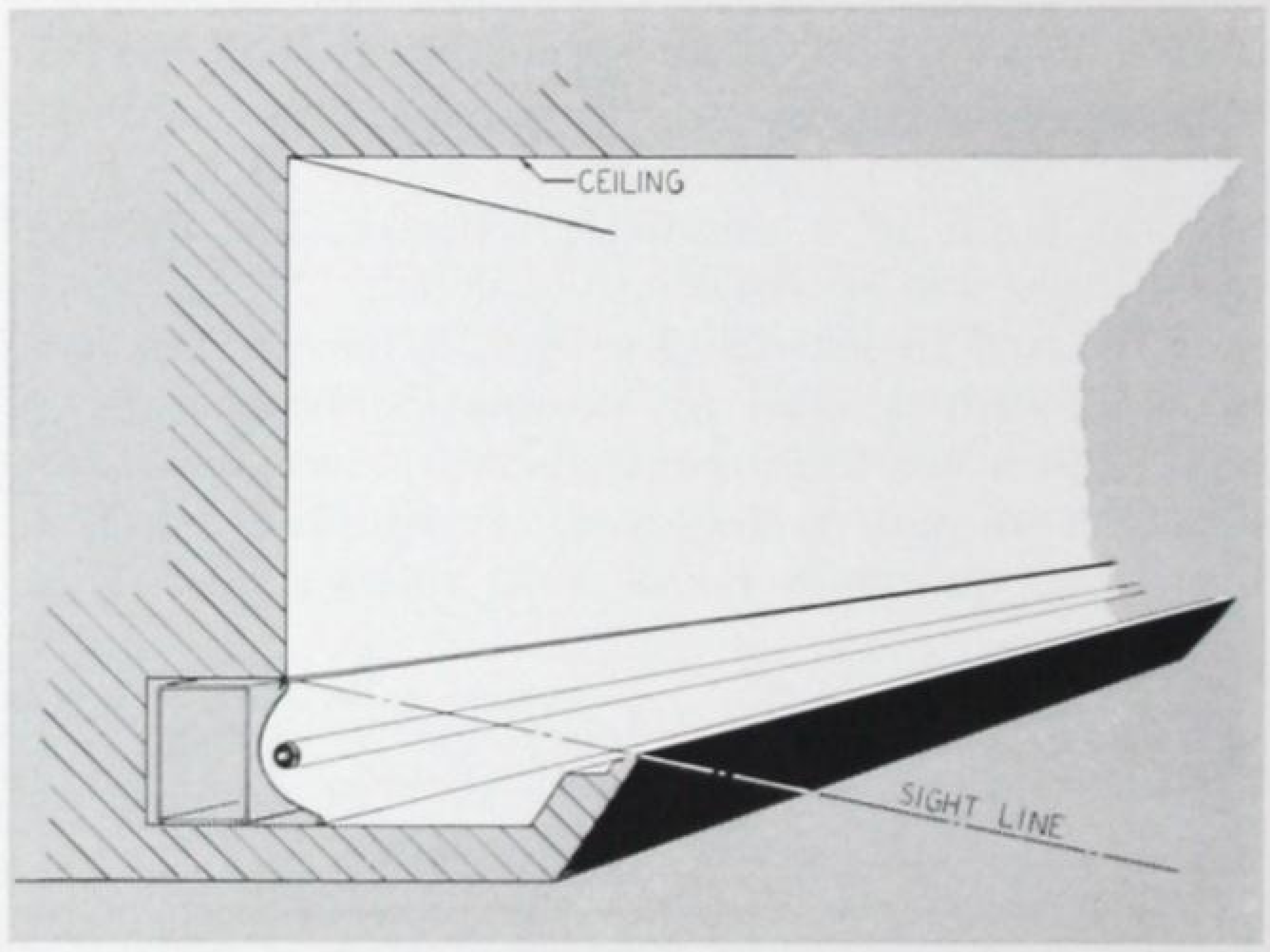


Fig. 59. Parabolic reflectors are used in this fluorescent cove lighting system.

Fig. 58. Plane and circular reflectors are used in this simple bracket luminaire for residence lighting.

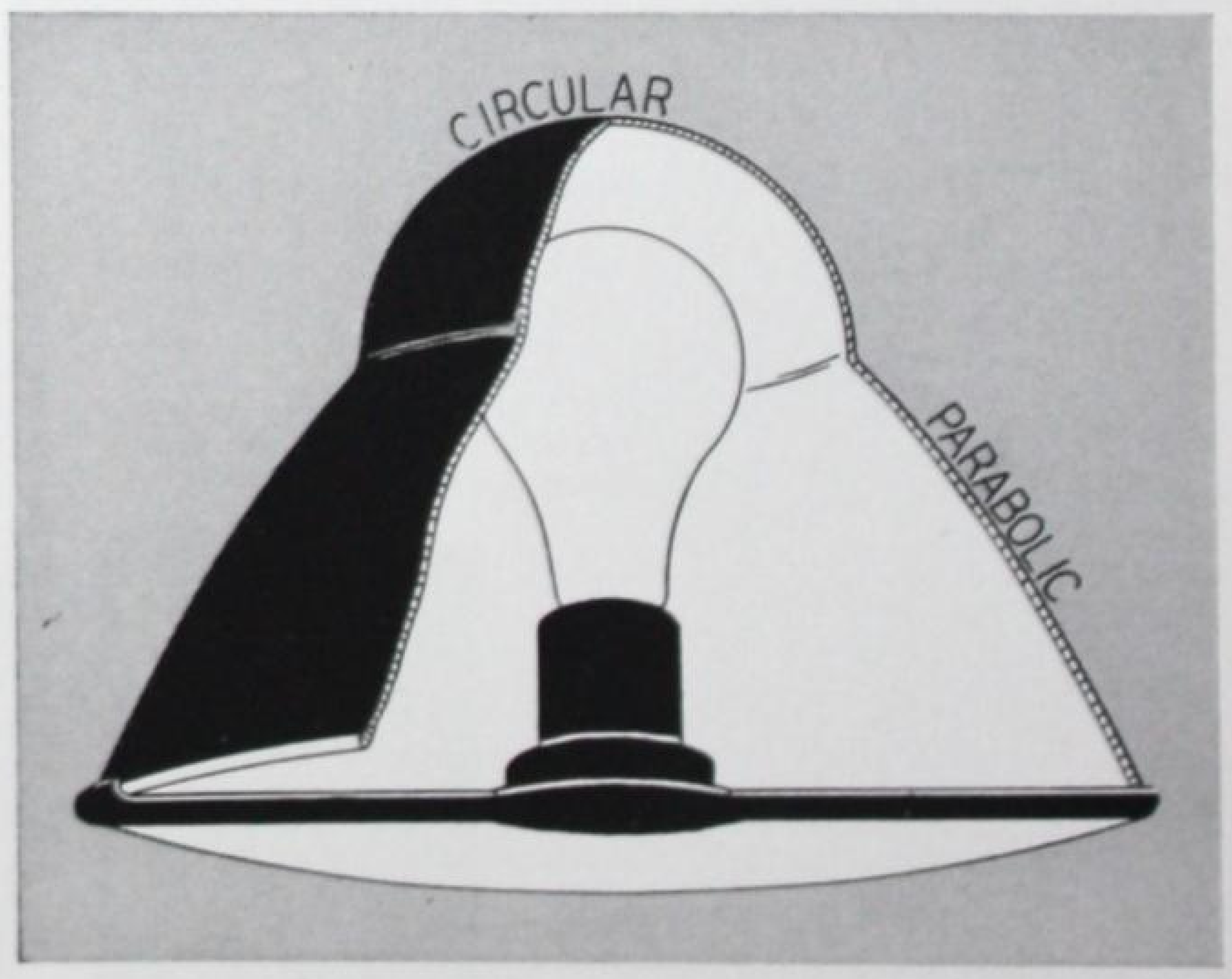


Fig. 60. A similar combination of circular and parabolic forms used with a filament lamp. The luminaire is a local lighting unit for industrial service.

THE ELLIPTICAL SECTION

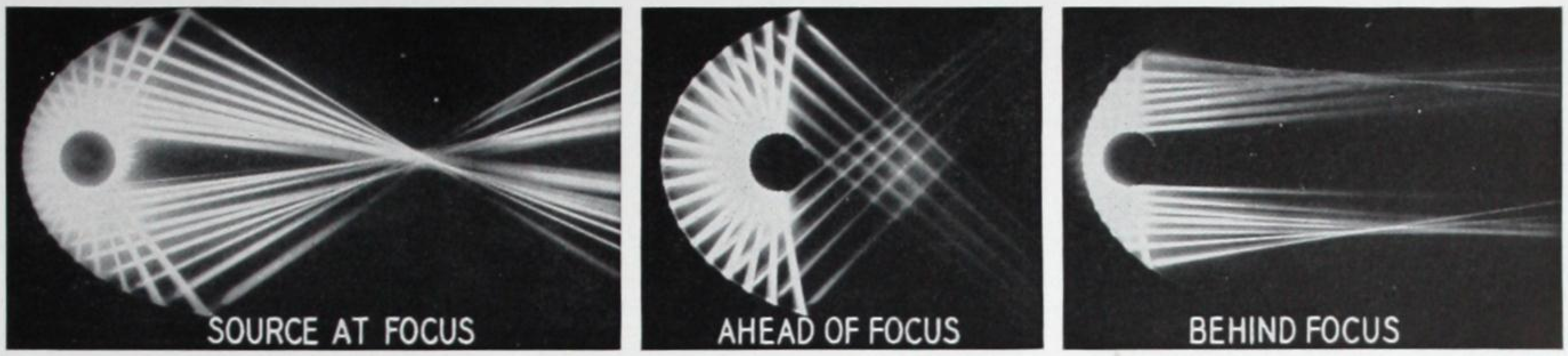


Fig. 61. **The Elliptical Section.** With an elliptical section if the light source is at one focal point the reflected rays will converge at the other, making possible the sending of a large amount of light through a very small opening as in "pinhole" downlighting systems. If the source is out of focus, convergence is sacrificed.

An ellipse is a curve of oval shape traced by a point so moving that the sum of its distances from two points remains constant (Fig. 63). If a concentrated light source is placed at one focal point in an ellipsoidal reflector, the reflected rays will converge at the other. This characteristic makes it possible to send relatively large amounts of light through very small openings, as in "pinhole" downlighting projectors. Or reflectors of this contour may be used in local lighting units of such focal distances that the work can be placed at the second focal point. As may be seen from the top illustration, if the source is out of focus, convergence is sacrificed. Such equipment must therefore be carefully designed and maintained.

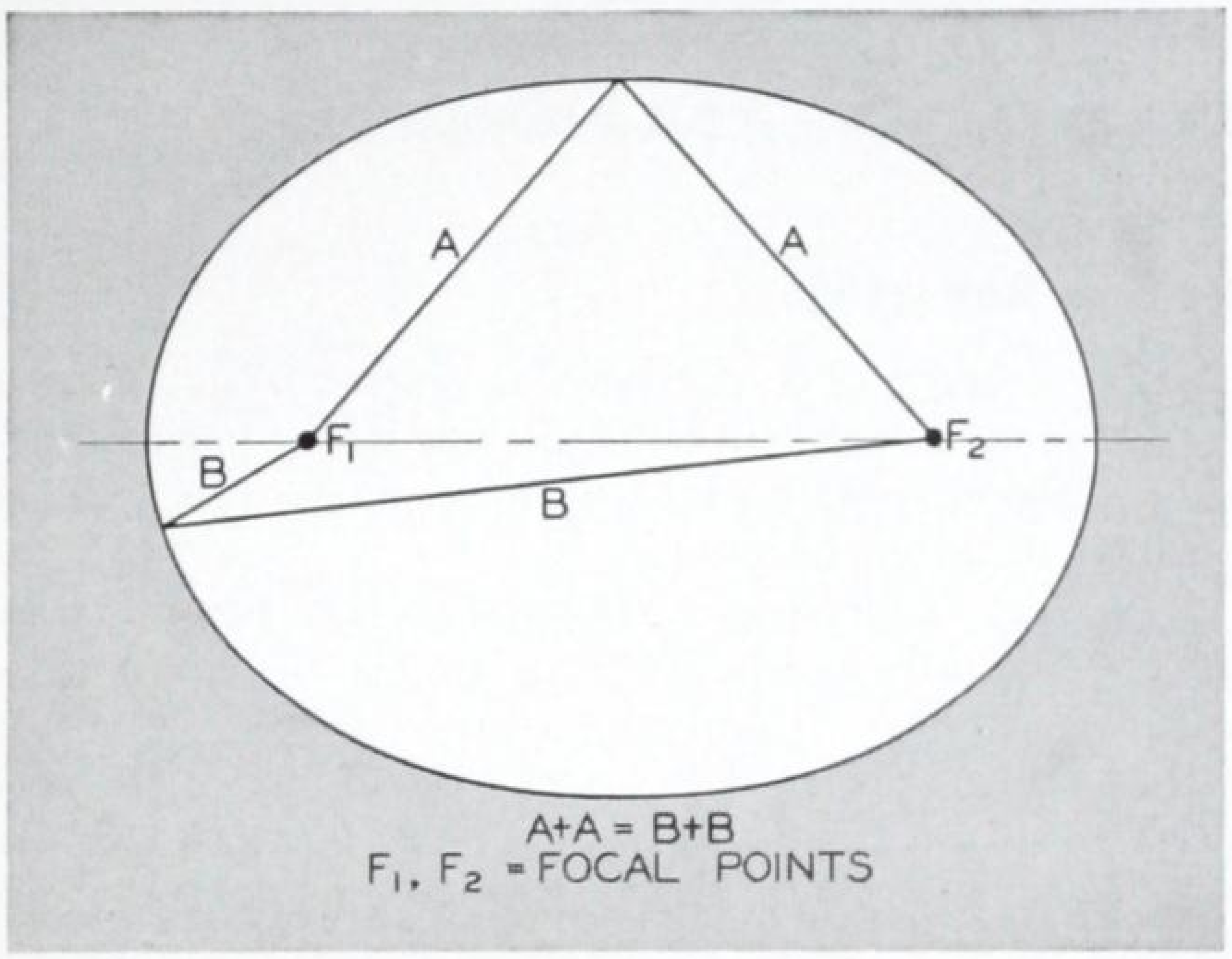


Fig. 63. There are two focal points in an ellipse (F1 and F2). The sum or the distances from these two points to any point on the curve is constant (A + A = B + B).

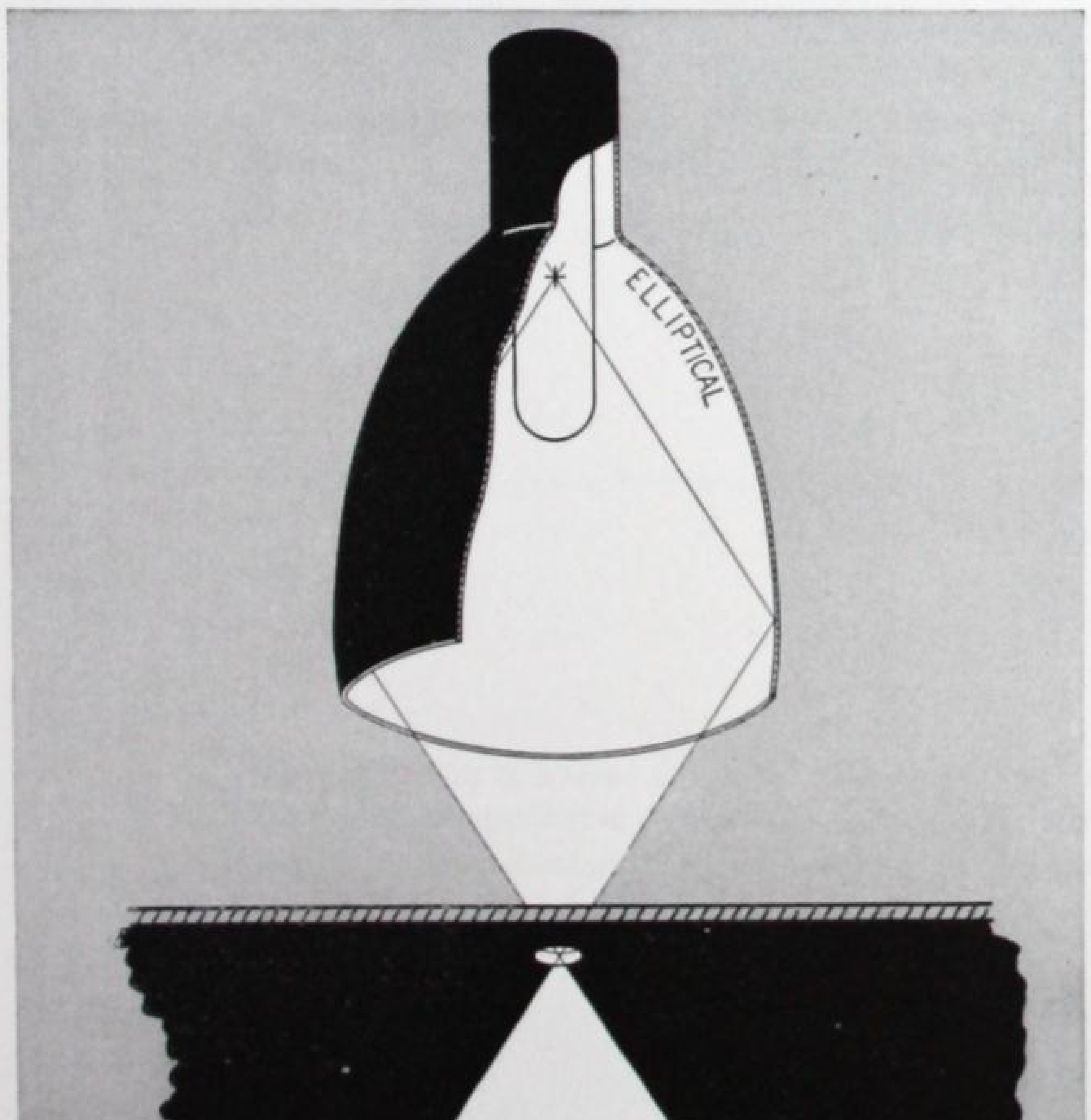


Fig. 62. In this theatre down-light or "pin-spot," the light-center of the lamp is at one focal point of the ellipse and the rays cross at the hole in the ceiling, which is at the other focal point.

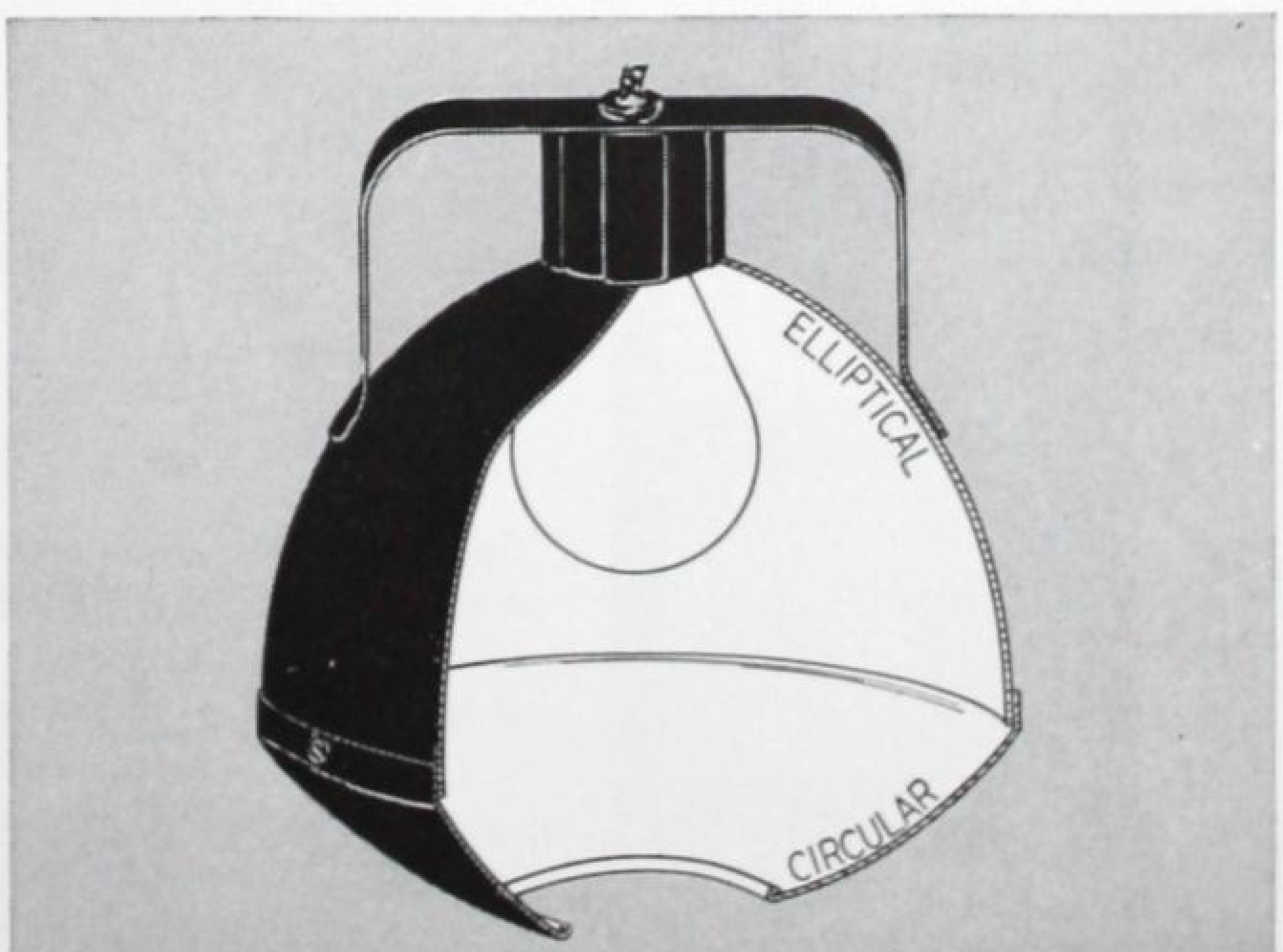
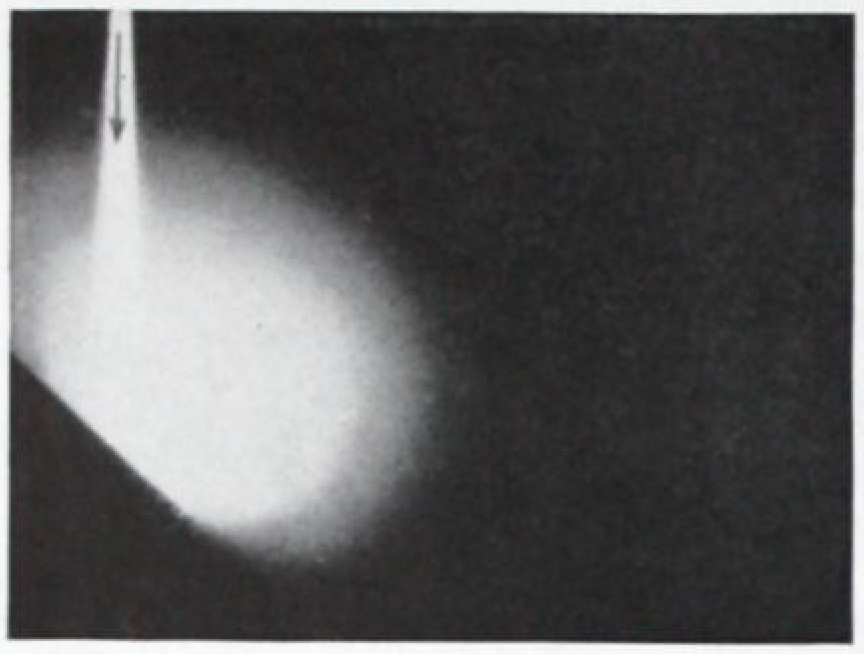


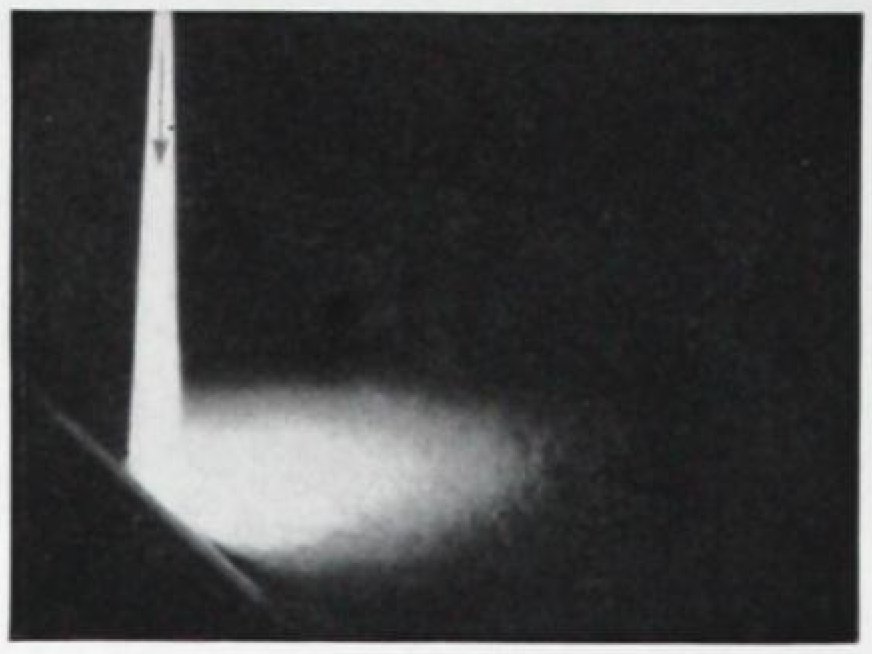
Fig. 64. Light and heat energy from the 10-watt heat lamp in this device are controlled by elliptical and circular reflectors. They focus on a point about one inch outside the opening at the bottom.

A



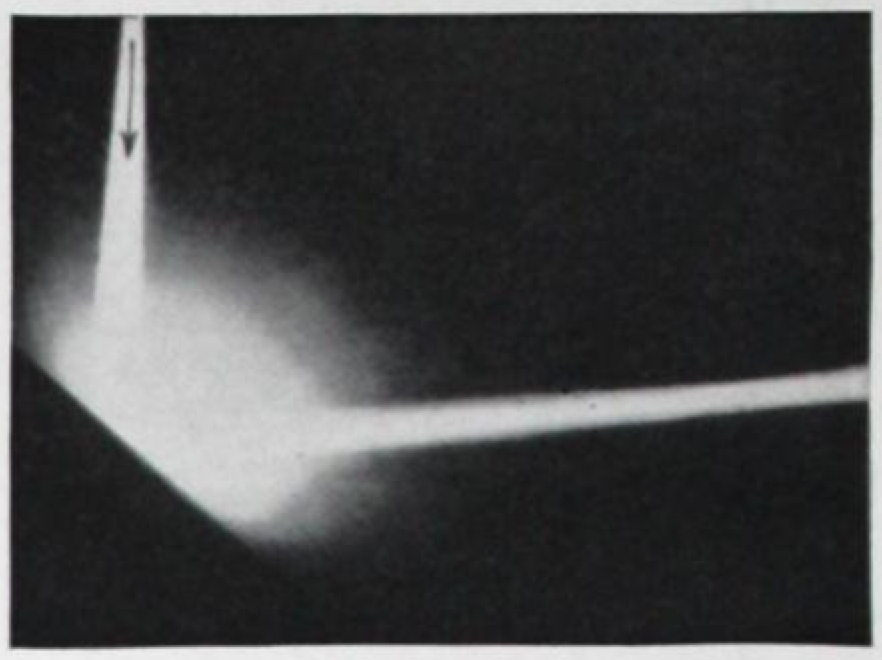
Mat paint,
Plaster, white
Blotting paper,
Terra cotta,
Limestone,
Sandstone
Magnesium Carbonate

B



Aluminum paint
Oxidized aluminum

C



Glossy porcelain enamel,
Calendered paper,
Gloss paints

Fig. 65. Characteristics of Diffuse Materials.

Diffuse Reflection

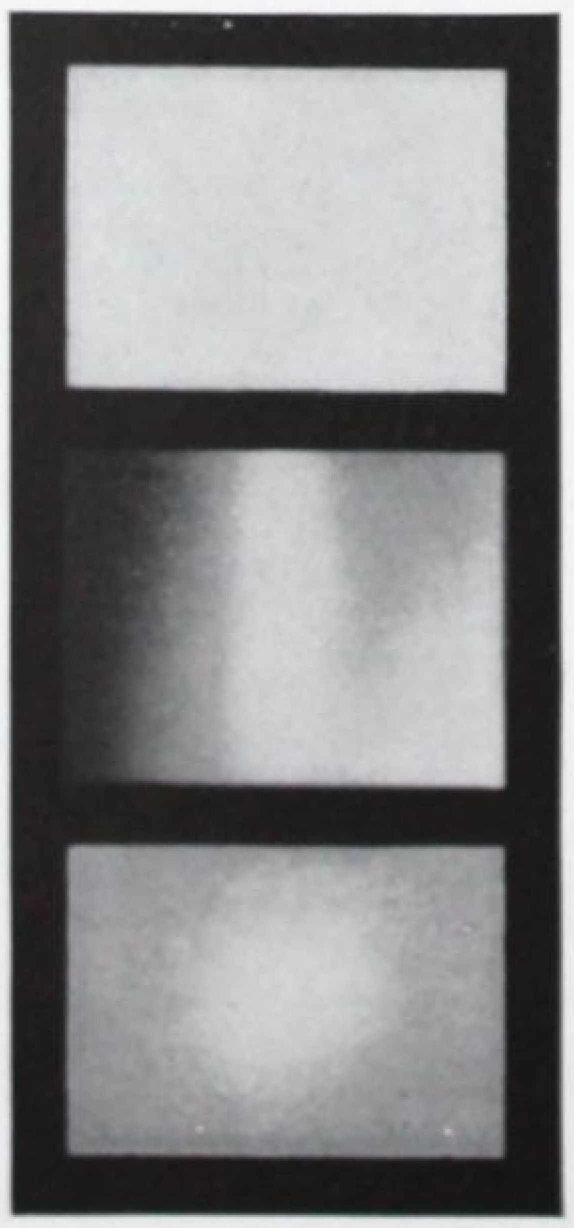
The foregoing discussion has emphasized the control of specular reflection. Other forms of light reflection—diffuse, spread, and diffuse specular, react in an entirely different manner.

Diffusely reflecting surfaces show no bright spots and are equally bright from all angles of view. Such a surface obeys Lambert's cosine law*, in essence, although no surface does so exactly. This is termed perfect diffusion; the light is reflected equally in all directions and there is no directional control (Fig. 65A).

Magnesium carbonate and white plaster are materials which have this characteristic. White and other mat paints such as are used for ceilings in interiors are similarly effective as diffusing media.

Reflecting surfaces which are etched such as oxidized aluminum or coated with aluminum paint create spread reflection which is useful in lighting design. They produce a beam characteristic as shown in Fig. 65B, having a maximum candlepower at the angle of reflection. Depolished metals have similar control characteristics.

Diffuse-specular surfaces such as porcelain-enamel, gloss paints, and calendered paper are in effect diffusing surfaces with shiny transparent coatings. They are equivalent to an ice-encrusted snow-bank or to plate glass placed over blotting paper or other dull-surfaced material. The light reflected specularly by such surfaces is usually of the order of 5 to 15 per cent of the incident light (Fig. 65 C).



A

Diffusely reflecting surfaces result in no bright spots and a surface that appears equally bright from all angles of view.

B

Spread reflecting surfaces spread the light so that the source is not definitely mirrored. But since the diffusion is incomplete, the surface brightness is definitely related to viewing angle. For example, aluminum painted surfaces appear bright at certain viewing angles and dark at others.

C

Diffuse-specular surfaces produce a bright image of the source on a luminous background of diffused light.

* See footnote, page 102.

TRANSMISSION

The measure of the ability of a medium to transmit light through it is called its *transmission factor* or *transmittance,* generally expressed in percentage.

Transparent materials such as clear, crystal sheet glass, or plastic permit the transmission of light with no appreciable change in its direction. This does not, however, mean that 100 per cent of the light is transmitted. In fact, if the incident light is normal to a clear glass surface, 80 to 90 per cent will go through, about 8 to 10 per cent will be reflected, and the remainder absorbed. The amount of reflected light depends upon the angle of incidence and may become a very high percentage for grazing angles.

Spread Transmission

For conventional luminaires, transparent materials have a very limited application. They are often etched or frosted to scatter or spread the transmitted light, as for example, in an inside-frosted filament lamp. In this case the degree of diffusion is not sufficient to efface the bright spot of the filament. It should be mentioned that a portion of the light is diffusely cross-reflected inside the bulb before it is ultimately transmitted. The resulting effect is called spread transmission.

Diffuse Transmission

Clear glass having an enamel or ceramic coating provides a transmitting medium which thoroughly diffuses the light. Similarly, cased or flashed opal glass and white homogeneous glass provide diffuse transmission. All of these glasses find considerable application in illumination, not only because of their transmitting properties but also for reflection characteristics. The properties of white glass may be most readily understood if it is regarded as ordinary glass in which fine white particles are held in suspension. Eight to ten per cent of the rays of light normal to a piece of white glass will be reflected from the polished front surface without entering the glass at all. The remainder travels through the glass until it strikes the white particles whence it is dispersed in all directions. Some of it is reflected as shown in Fig. 66.

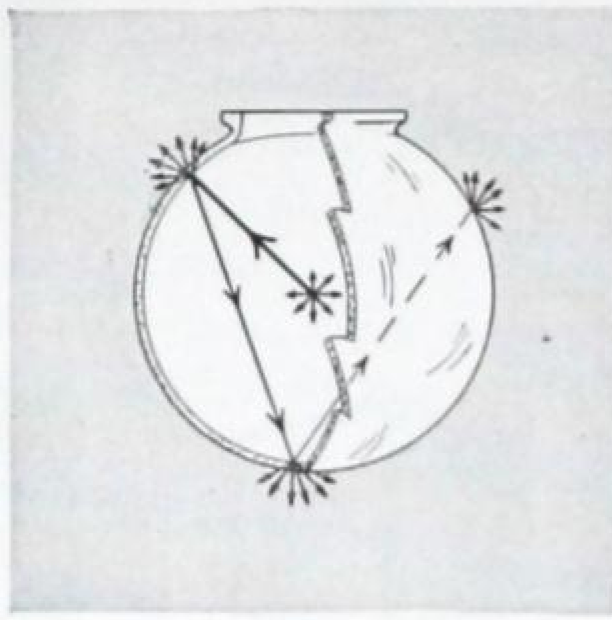


Fig. 66. Cross reflections in an enclosing luminaire.

If any light ray passes through the glass without striking a white particle, it goes out in a line parallel to the one along which it entered. When this occurs, the white glass is not completely diffusing, and if, for example, it is in the form of a globe or cylinder, the outline of the lamp could be seen more or less clearly. This condition would be present even though only 1 per cent of the light passed through unchanged. See spread transmission materials, Fig. 67.

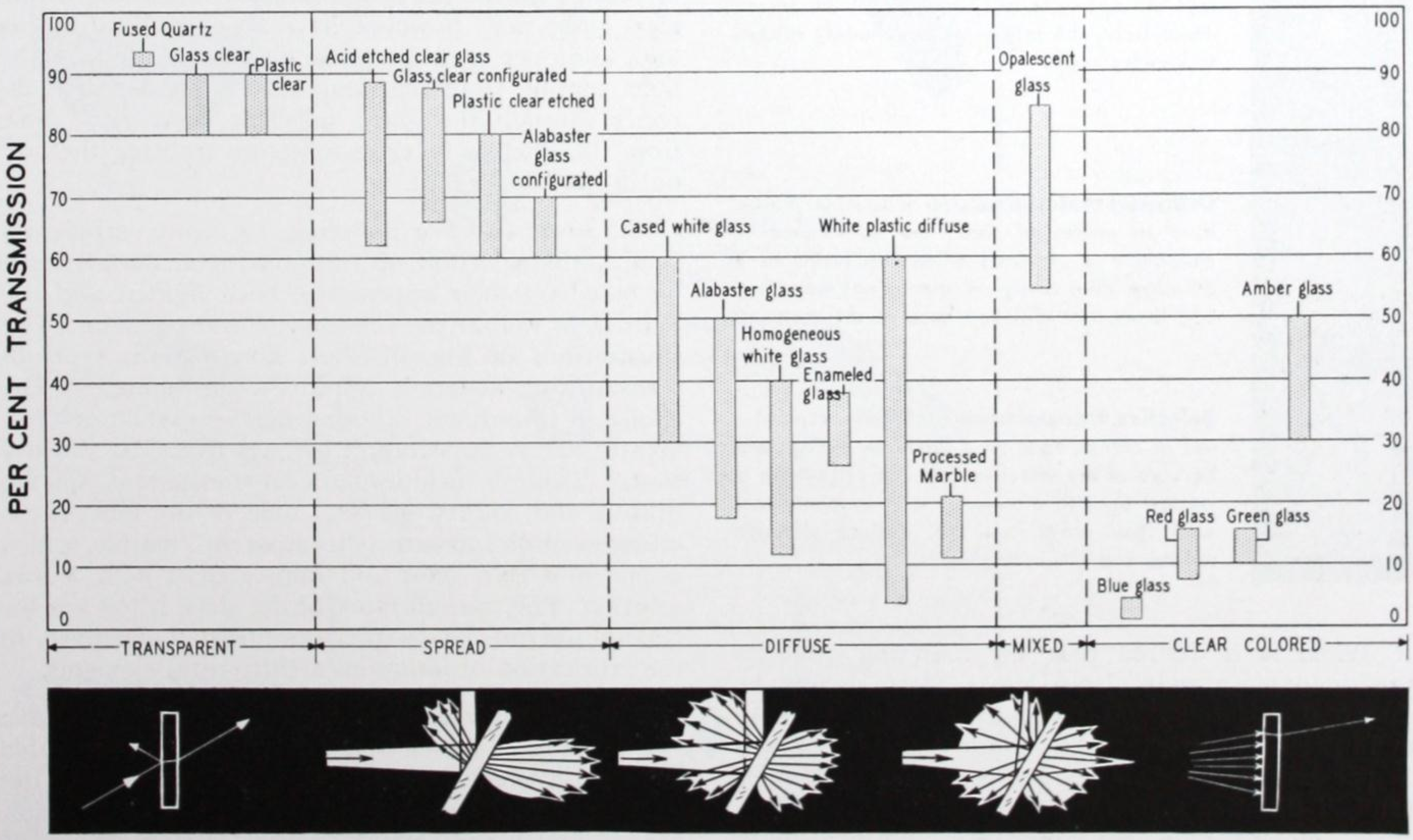


Table 5. Transmission characteristics of materials.

APPEARANCE OF TRANSMITTING MATERIALS

To insure satisfactory results, the selection of light-control materials must be based on their appearance, lighted and unlighted, and the efficiency of transmission. The illustrations show how the various types of transmitting materials appear when lighted. Table 5 gives a summary of transmission efficiencies.

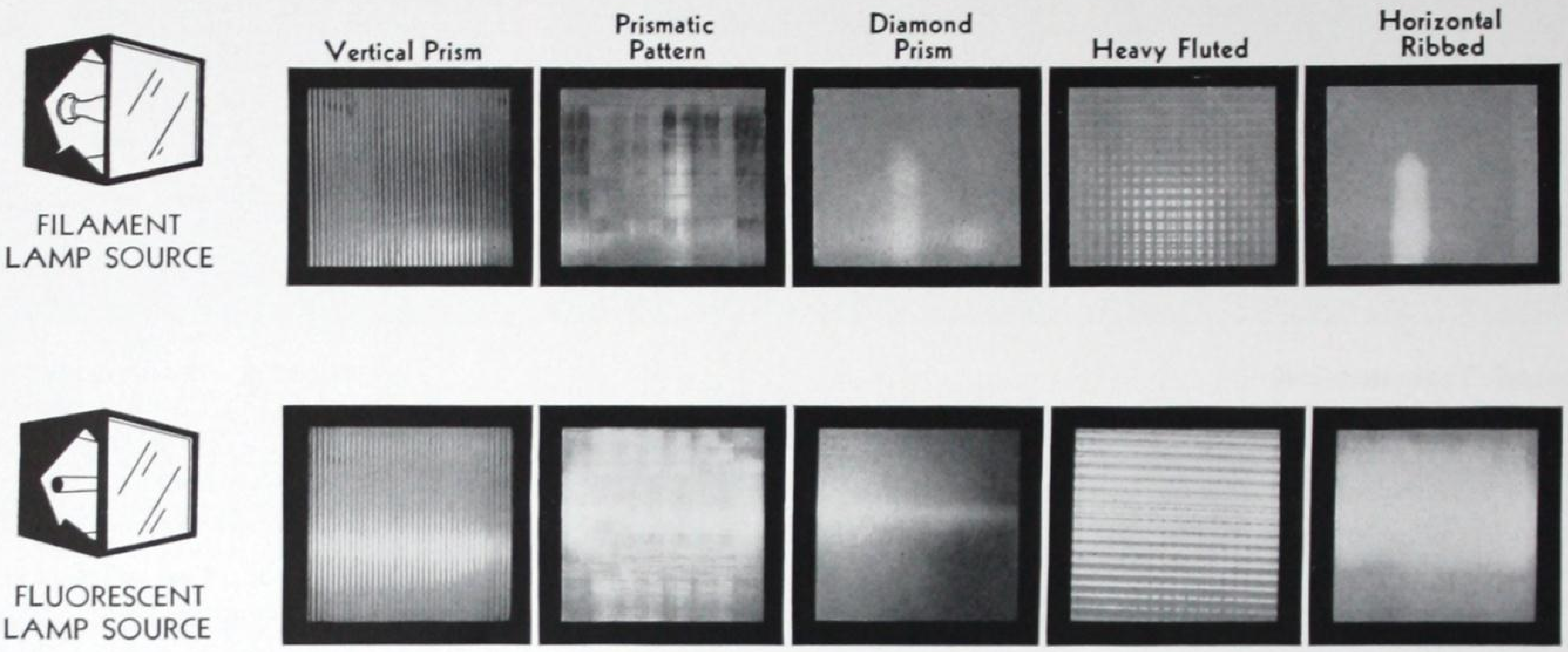


Fig. 67. **Prismatic Glass** may be used to produce banded effects and interesting patterns, particularly with various colored lamps. Ribbed glass produces a banded effect at right angles to the ribbing.

Spread transmission materials spread the rays but not sufficiently to conceal the source completely; the brightness is definitely related to viewing angle.

Diffusing materials appear of equal brightness from all angles of view; the appearance of uniformity is obtained when the lamps in a diffusing white cavity are spaced not more than 1½ times their distance back of the material.

Selective transmission materials result in a red or orange spot on a luminous background because of the selective diffusion. If a lamp is viewed through a material such as opalescent glass, the image will be distinct although reddish and low in brightness.

When it is desired that the reflecting qualities predominate, a very dense white glass should be chosen, that is, one which transmits not more than 10 to 15 per cent. Such a glass would probably absorb 15 per cent, and reflect 75 per cent. On the other hand, if diffusion is the main objective, as in an enclosing globe for filament lamps or a cylindrical luminaire for fluorescent tubes, the glass should have a maximum transmission without revealing the outlines of the light source. This limits the transmittance to about 50 or 60 per cent. A totally enclosing white-glass globe may, however, have an over-all output as high as 85 per cent, for while only 55 per cent of the light coming from the lamp may be transmitted directly through the glass, sufficient light may come from the interior by cross reflection to bring the output up to 85 per cent.

As with reflecting materials, to insure satisfactory results, the selection of transmitting materials must be based on their appearance both lighted and unlighted, as well as the efficiency of transmission. The illustrations of Fig. 67 show how various types of transmitting materials appear when lighted. The choice of illuminant, whether filament or fluorescent, greatly affects appearance, as seen from the illustrations. Table 5 includes data on transparent, spread, diffuse, and colored glasses. One of the most interesting examples shown is "transparent" marble, which is cut into thin slabs and impregnated with a wax solution. The transmittance of the stone is too low for general use but the designer can utilize it effectively in the fabrication of luminous architectural elements.

Many transparent and translucent materials have the properties of selective transmission or selective absorption which permits only certain sections of the spectrum to pass through them. The most common are colored glasses which transmit certain colors of visible light and absorb the others.

A more complex form of selective transmission is found in Nature in the earth's atmosphere and accounts for the color of the sky. The light from the sun is polychromatic, that is, it consists of all the colors of the rainbow—violet, blue, green, yellow, orange, and red. The earth's atmosphere scatters the blue light from the sun more strongly than the other colors which make the sky appear blue on a clear day. Dust particles in the lower atmosphere have a different effect; when the rising or setting sun is observed, it appears red. When the scattering particles are of the same size, such as water droplets, the effect is the same for all colors and the clouds, which consist of vapor particles, appear white.

ABSORPTION

Sunlight on a tree produces a natural example of several phenomena, notably *absorption*. The average tree's branches and green leaves reflect about 3 per cent of the sunlight which strikes them, absorbs about 87 per cent. Instead of 10,000 footcandles on a midsummer day, the illumination in the shade is therefore about 1000 footcandles, the light energy absorbed being converted into heat. A tree with usual foliage could thus be said to have an absorption factor of 87 per cent, a reflection factor of 3 per cent, and a transmission factor of 10 per cent.

Ordinarily, the absorption of light flux by reflectors, shades, louvers, and baffles, as illustrated in Fig. 68, is considered a disadvantage since it affects the efficiency adversely. In designing luminaire appurtenances, it is usually desirable to choose a material or finish which will reflect and diffuse the light efficiently rather than one which will absorb nearly all the light or a considerable portion of it. However, utilizing dark colors on such media is often the simplest method of controlling "stray" light or light which may be projected or reflected in undesirable directions.

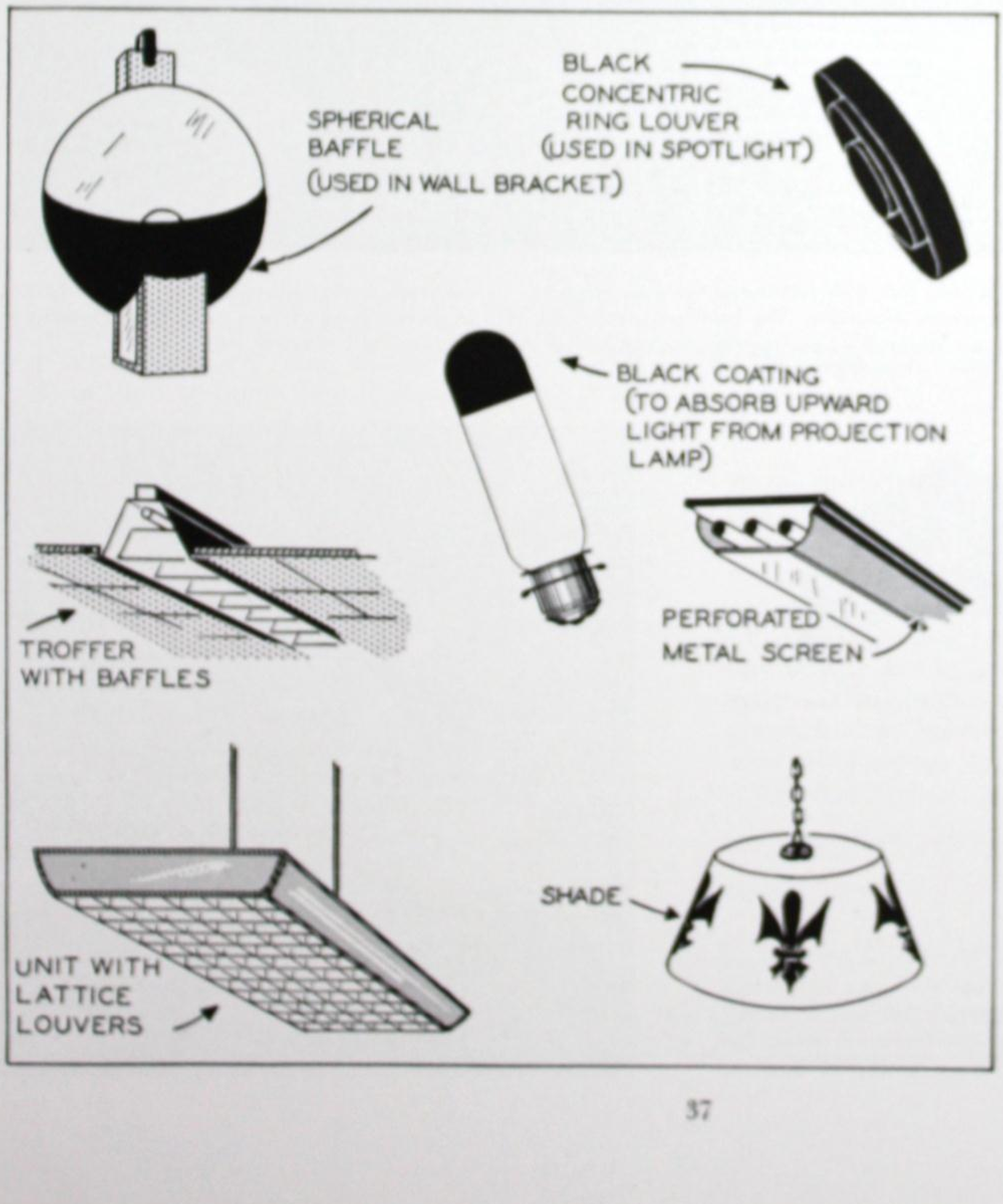
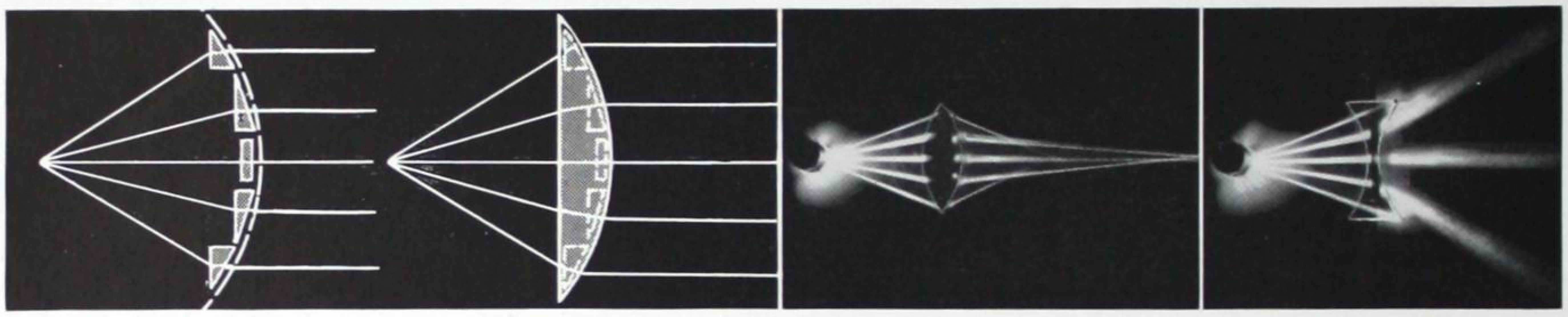


Fig. 68. Shades, shields, and lattice-louvers are used in lighting equipment to absorb and redirect light into useful directions.

REFRACTION

When a reed growing out of a pond is viewed at an angle, the stem appears to bend at the surface of the water. This is due to the fact that the speed of light in water is at a different rate than its speed in air. The phenomenon is called *refraction.* A common source of "rainbow" refraction occurs when bare (clear bulb) filament lamps are used in a crystal chandelier. Each crystal of glass in the chandelier creates numerous small rainbows all of which are blended into the usual white light. The "white" light from the lamp enters the crystal and the various colors are emitted at different rates of speed. The path of light is also bent out of line if the light projects through at an angle. The degree of bending depends upon the angle and the relative density of the medium such as might be encountered with crystal or other forms or combinations of glasses, or with plastic or fused quartz.



A lens may be considered as simply a built-up system of prisms. The two illustrations at the left show such a prism system and a single convex lens built up from that system. At the right are shown convergence with a double convex lens and divergence with a double concave lens.

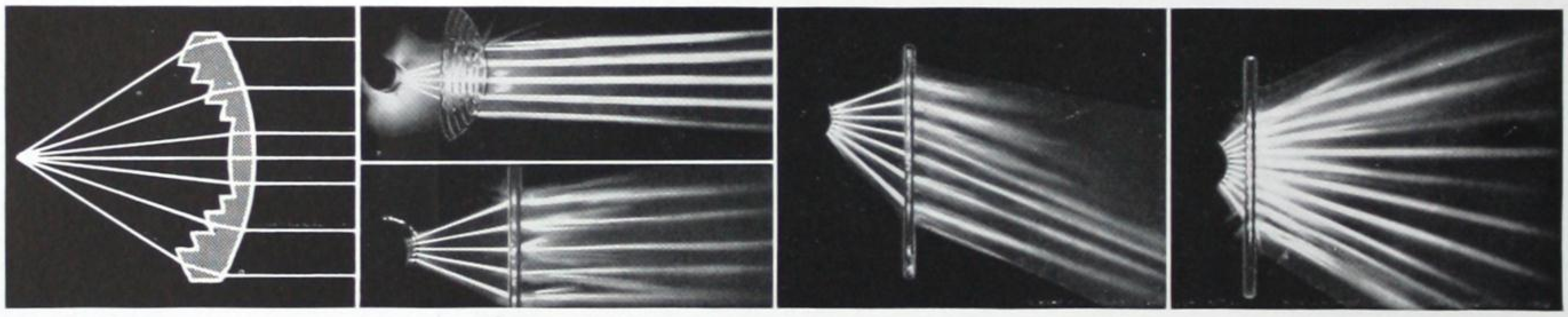


Fig. 69. A Fresnel lens consists of a convex lens with sections of the glass removed. In the small illustrations are shown the distribution from a typical Fresnel lens (top) and a prismatic lens plate. The latter are used extensively in downlighting systems. The other illustrations show how varying beam distributions can be obtained by placing the source either off center or closer to a prismatic lens plate.

The Lens

Accredited by many scientists to be the one invention contributing most to scientific knowledge, the lens is probably the instrument most commonly used to refract light. The most familiar example is the eyeglass. The optical profession utilizes the refractive power of a lens to compensate for eye defects by changing the direction of light entering the eye. By various combinations of thickness and contour of the glass, the non-symmetry of the lens of the eye and the cornea (the outer transparent layer of the eye-ball) are compensated.

Types of lenses used in projection equipment are shown in Fig. 70.

Fig. 69a. The clear-glass lens plates in the fluorescent luminaire sections for general lighting are each four feet long and fifteen inches wide. The square lens-plate sections for accent lighting contain filament lamps and hemispherical reflectors above them. The reflectors are positioned to direct the beams to special displays.

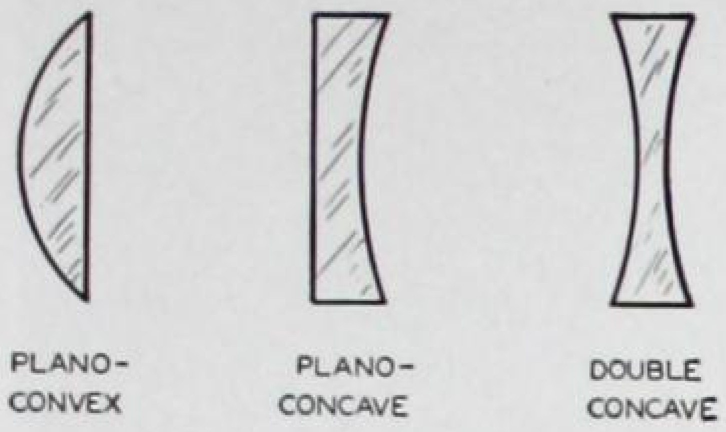


Fig. 70. Types of lenses used in optical instruments.

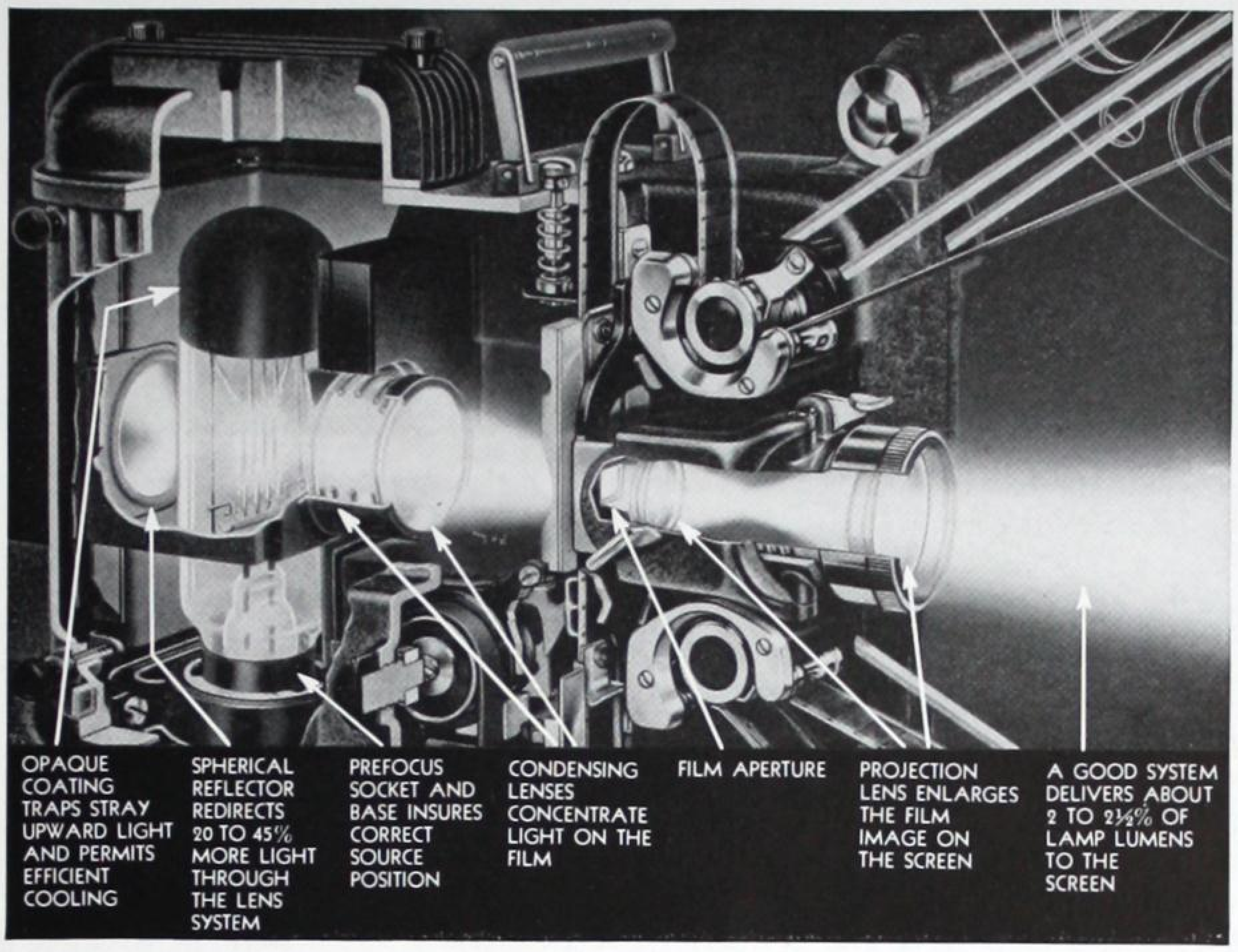


Fig. 71. Essential optical elements for motion picture projection.

The Prism

A special form of refractor is the prism, which resembles the chandelier crystal in action. When a beam of light is projected through the face of the prism, the emitted light is in the form of a rainbow "ribbon." This spectrum, called the visible spectrum, is reputed to have been discovered by Sir Isaac Newton. By internal reflection a right-angled glass prism can return light through an angle of 180°, as shown in Fig. 72. Reflection at other angles depends upon the slope of the prism surfaces. Materials vary in their refractive power, due to the difference of the speed of light through them. The refractive power is described as the *index of refraction,* in terms of the relative speed of light through air. Water and plastics have lower indices of refraction than glass.

A prism is in one sense a section of a plano- convex lens. An interesting and useful light control device called the plate-lens results when a flat plano- convex lens is developed as a series of ring-lenses, as shown in Fig. 74, and used in a "downlight." Painting the risers of a lens-plate a pastel color gives the plate an interesting decorative appearance when viewed at an angle, without reducing the efficiency to an uneconomical degree.

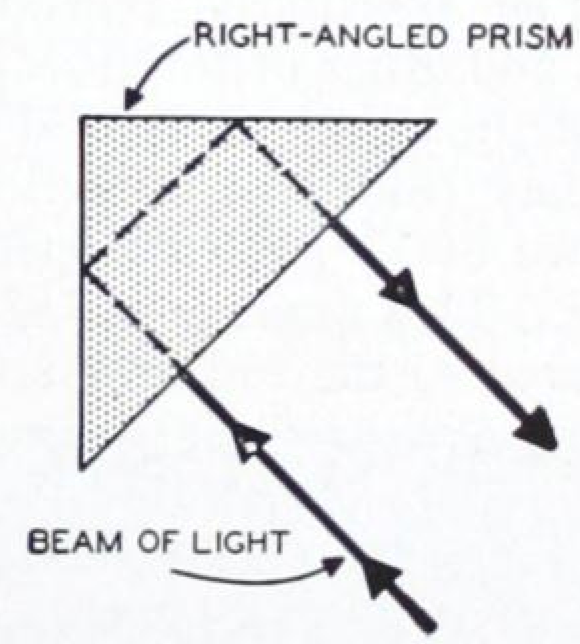


Fig. 72. Right-angled prism.

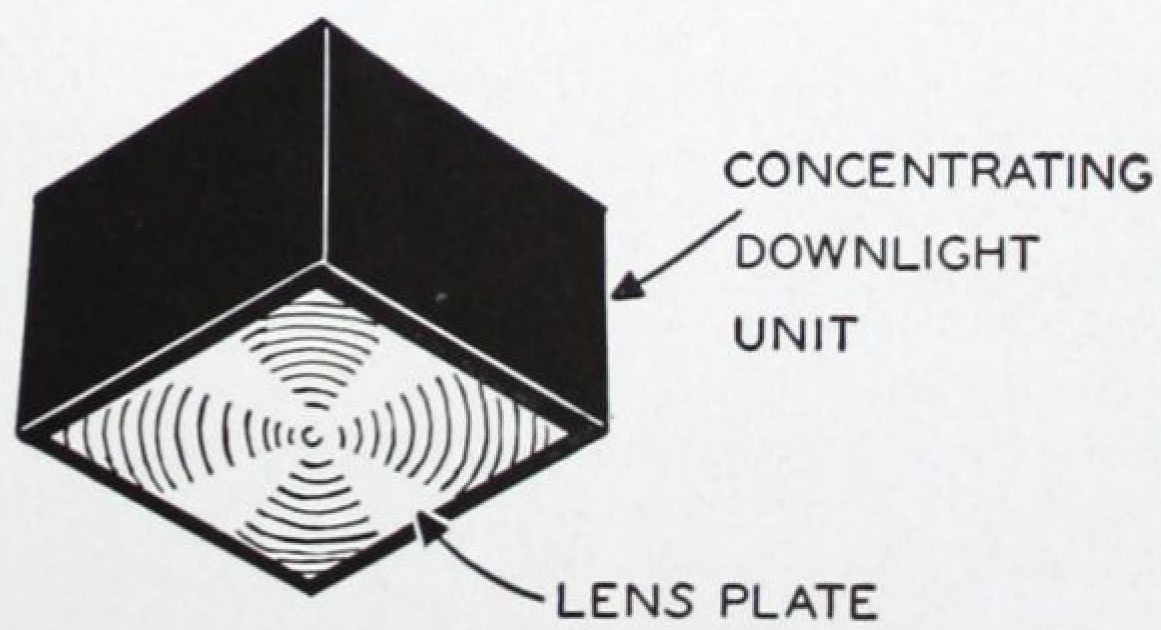


Fig. 73. Downlight using a plate-lens for light control.

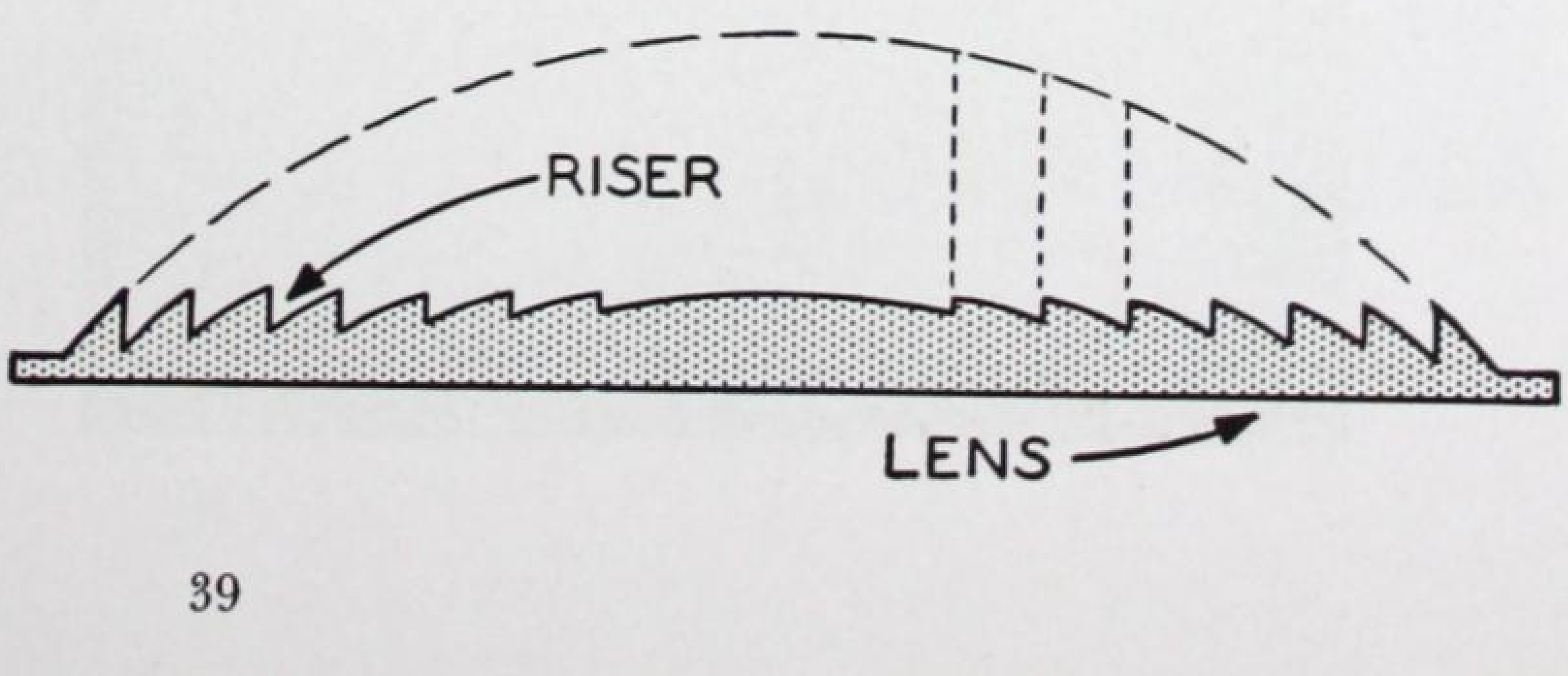
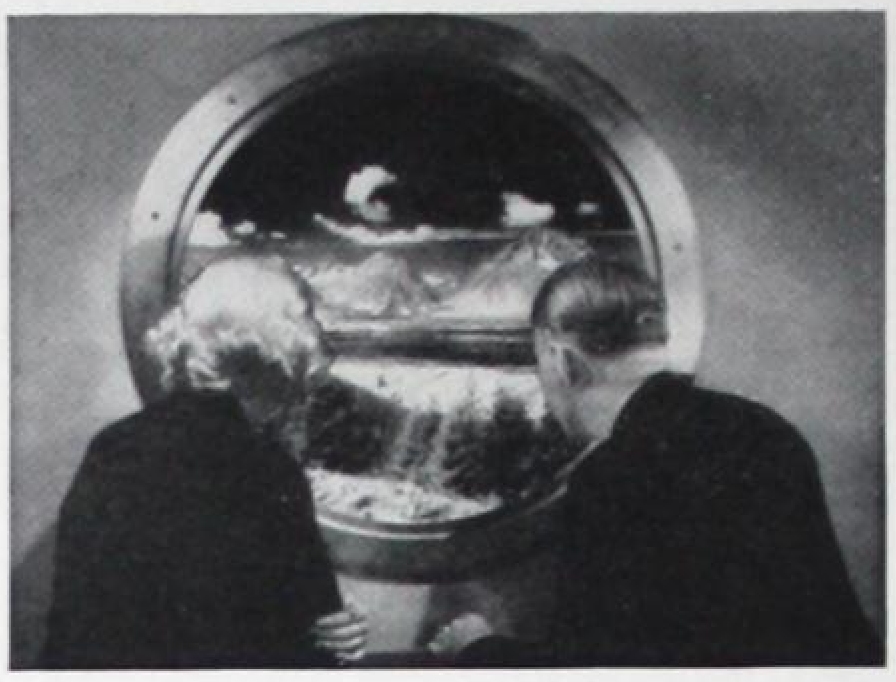


Fig. 74. Development of a Fresnel lens. The slope of the ring-lens sections corresponds to those of a thick plano-convex lens.

When the outside view is too bright . . .



a turn of the control knob of the Polaroid Sight-Conditioning window brings brilliance down to the comfort level . . . . .

or if you tire of the view another turn cuts it off altogether.

POLARIZATION

Conventional light sources are regarded as radiators of light flux which "vibrates" in all planes at right angles to the direction of the light beam. Many materials have the capacity to screen out these vibrations in one plane and the resulting beam is said to be partially "polarized."

A few materials have the characteristic properties of screening out all the so-called vibrations except those in one plane and this is said to be complete polarization. The specularly reflected light from paper, linoleum, and other materials is partially polarized; for example, a beam of light directed upon a clean plate of glass (index of refraction, 1.54) at an angle of incidence of 57°, the reflected light is completely polarized. This angle is called the polarizing angle and is related to the index of refraction by the formula:

$$n = \tan a$$

where n is the index of reflection of the glass and a is the polarizing angle. The tangent of $57° = 1.54$.

Thus when looking through a polarizing filter or screen at a reflection produced on glass at the polarizing angle, the reflected beam can be obliterated by arranging the polarizing axis of the filter at the proper angle. The effect is reduced glare and improved visibility.

Screens of such polarizing material have been applied to eye-glasses, used as filters in camera lenses, used in large sheets for variable screens in modern railway club-cars, and in a wide variety of optical instruments. The transmission factor of the material ranges between 25 and 42 per cent; hence, when used on a camera lens, for example, a larger stop-opening is necessary. Polarizing apparatus is used principally in scientific work and critical inspection process, and it is extremely valuable in these fields. One interesting use is in the inspection of glass phials (Fig. 76) and other transparent articles; when viewed under polarized light, strains in the product are indicated by a series of multi-colored bands.

Fig. 75. Source reflections on glossy paper are eliminated by polarized light.

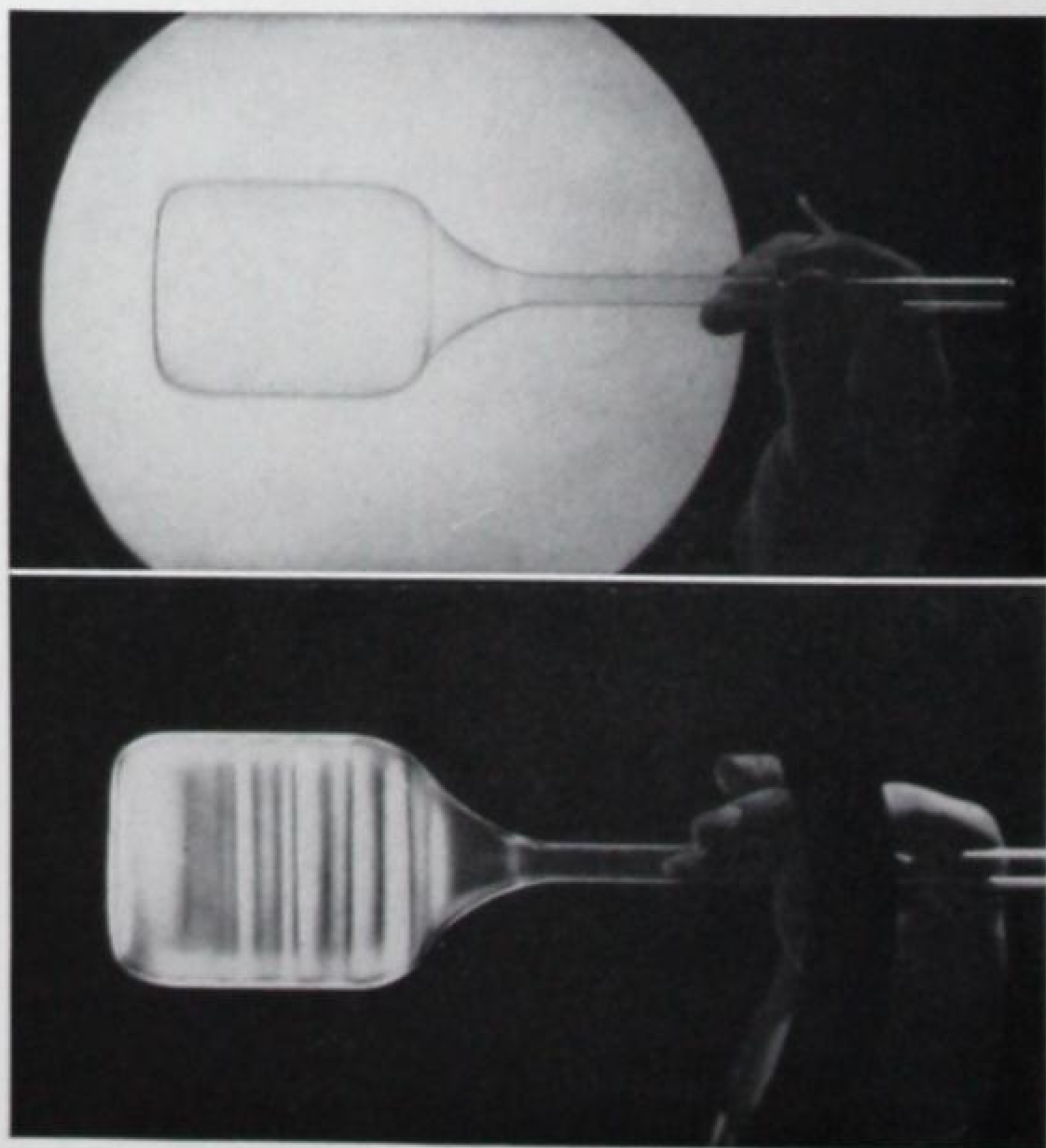


Fig. 76. Upper photo ordinary light. Lower photo polarized light.

PART VI
LIGHT AND COLOR

Color is a fundamental consideration in the study of light and lighting effects. Light and color are closely related; in fact, the color of an object is defined as *the capacity of the object to modify the color of the light incident upon it**.

The interdependence of color and light is a vital factor in a large number of seeing tasks in industries, arts, and crafts. Moreover, for general lighting design, it is obvious that the reflectance values of ceilings, walls, and other surfaces in the room depend upon the colors used and accordingly affect the utilization factor of the illumination system. These color values not only establish the general color appearance or "color scheme" of the interior but in a large measure the brightness ratios in the immediate seeing zones, thus affecting the "visual efficiency" of those who work in the room. Color, therefore, has its practical application in seeing and also its effect is one of psychological significance. Color creates definite decorative "moods" and may be said to provide psychological "warmth," "coolness," and other attributes of this nature.

Color Temperature

Warm and cool colors of light sources are also expressed on a color temperature scale. Color temperature** describes the absolute temperature in degrees Kelvin of a theoretical blackbody radiator whose color matches the source in question. Such a body is black at room temperature, red at 800° K, yellow at 3000° K, white at 5000° K, pale blue at 8000° K, and brilliant blue at 60,000° K. The laboratory device used for tests resembles a miniature electric furnace.

Representative values of sources are: candle flame –2000° K, gas-filled lamp–3000° K, 500-watt daylight filament lamp–4000° K, daylight photoflood lamp–5000° K, daylight fluorescent lamp–6500° K.

Primary Colors of Light

Contrary to popular belief, the primary colors of light are red, green, and blue. Red and green light together make yellow light. Mixing red and blue light produces reddish-purple or violet light. Combining green and blue light produces blue-green. The combination of all three primaries—red, green, and blue—produces white light. This addition might be expressed mathematically by the formula: $x + y + z = 1$, in which x, y and z are the three colors of light whose addition produces unit color, white (Fig. 77).

* See Glossary, page 85   ** See Glossary, page 86.

Fig. 77. The primary colors of light are red, green, and blue. Mixing the primary colors of light produce white light, combining colors in pairs produce violet, blue-green, and yellow.

It is interesting to note that light can be subtracted as well as added or mixed. This phenomenon may be illustrated by placing magenta (bluish-red), yellow, and blue-green filters over a "white" source of light, arranged as shown in Fig. 78. In the center where the three color screens are superimposed, the filters absorb all light. This technique of applying color screens, using the subtractive method, is applicable in stage and show window lighting systems. It is also valuable in solving special problems of color-matching in which the color of daylight is produced by filament sources equipped with suitable filters in so-called color-matching luminaires, as shown in Fig. 79.

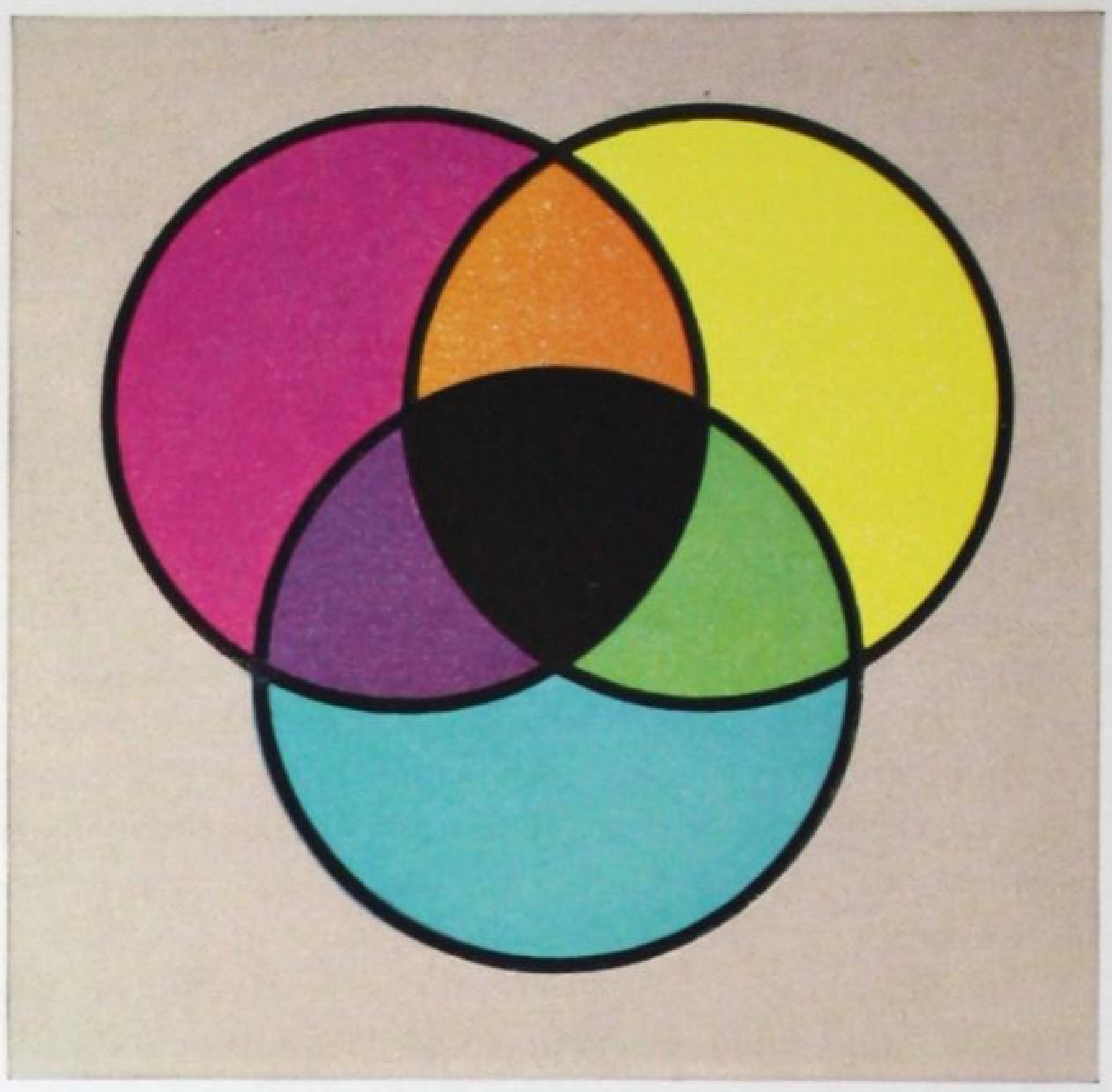


Fig. 78. Mixture by subtraction — the three color screens together produce black.

Fig. 79. An air-cooled color-matching skylight providing diffused north sky daylight of approximately 7500° K and horizon sunlight of approximately 2500° K (color temperature). The daylight quality is produced by 1000-watt inside frosted lamps, color-corrected by filters; the horizon sunlight by neck-silvered lamps operated two in series.

Color and Colorants

Substances which are used to produce surface colors in objects are called *colorants**. They include dyes, pigments, paints, inks, and all decorative coatings. In the industrial field, the use of colorants in manufactured products has increased greatly in recent years. Modern package-goods, textiles, and automotive products, to name only three, use several thousand tints and shades of colorants and a trained colorist is capable of identifying all of them. *Tints* of color are usually considered to be the result of mixing white with a color. *Shades* of color are produced by mixing black with the color.

Colorants are prepared by mixing pigments. In the most elementary form, the primary colors are *red, yellow,* and *blue,* mixtures of which result in secondary or intermediate colors. Mixing red and yellow pigments produces an orange colorant. Red and blue produce purple; yellow and blue produce green. Mixing all three—red, yellow, and blue produces black. This might be expressed mathematically by the formula: $a + b + c = 0$, in which a, b, and c are the three colorants whose addition produce zero color, black. Painters and decorators generally work with tints and shades of colorants. Printers, however, are more likely to employ the primaries red, yellow, and blue which with black produce a gamut of color in the four-color printing process.

Color Systems

There are numerous systems of specifying color. They all attempt to simplify the approach to this complex subject, and some present principles of color harmony. Color systems may be generally divided into two types: (1) those which specify color in terms of a set of "standard" colorants such as printed color-plates or "color chips," and (2) those which specify color in terms of a mixture of theoretical colored lights.

* See Glossary, page 103.

Color samples of paint, lacquer, and similar colorants are commonly published on cards or folders by individual manufacturers and these generally have *name* classifications referring to the particular product. The name specification method is used widely in industrial and commercial fields and is highly complicated by the multiplicity of color names. Some of the names are well established, such as Prussian Blue and Chinese Red, as used by artists. Other more modern names such as Bombardier Blue and Angel Pink endeavor to imply attributes to specific products and are coined principally for the advertising value their uniqueness may lend.

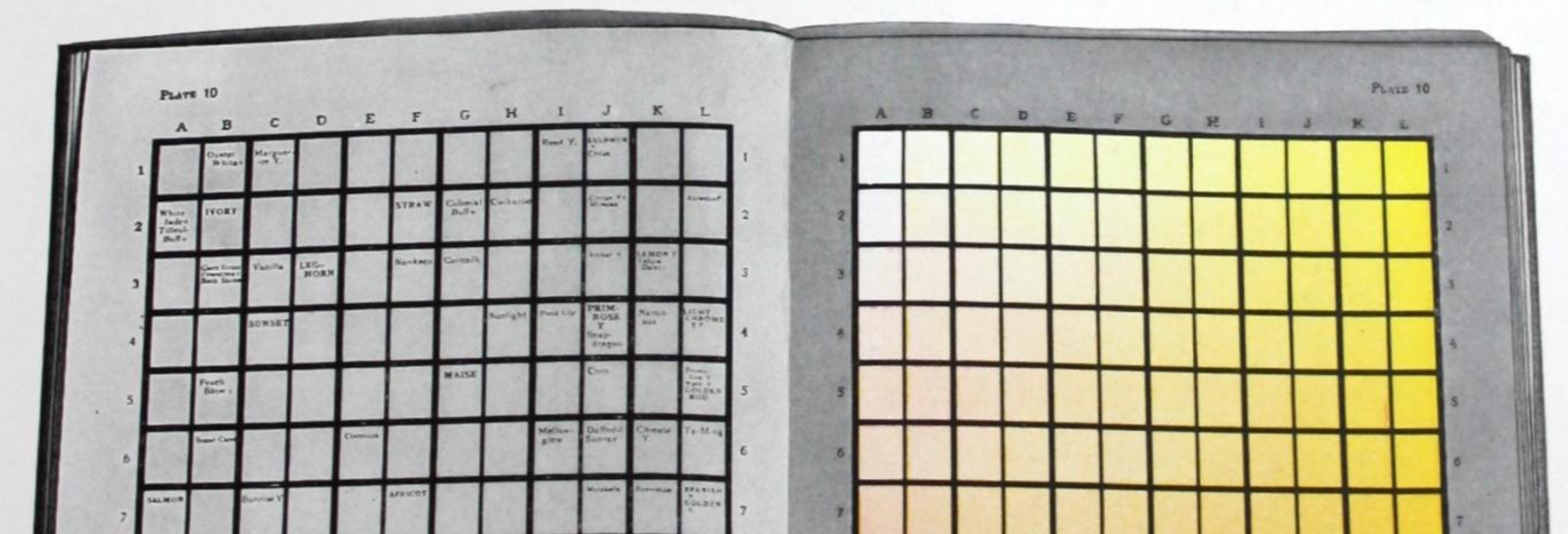
Some color systems useful for study are the Color Dictionary, the Munsell System, the Ostwald System, and the I.C.I. Chromaticity Diagram.

Color Dictionary

The Maerz and Paul Dictionary of Color*, accredited by scientific authorities as the foremost text on color names, is particularly helpful in the study of the general subject of color nomenclature. The book contains 7000 different color samples and lists about 4000 color names. Samples are arranged in an order following the spectrum, in seven main groups: Red to Orange, Orange to Yellow, Yellow to Green, Green to Blue-Green, Blue-Green to Blue, Blue to Red, and Purple to Red. In each group, all the colors between the stated terminals are printed on a single color plate, graded by small degrees from the full strength of the colors into white. Each group is given eight successive plates; the first plate in full purity, the seven following plates, ever-increasing amounts of gray, until the colors approach black. The color plates are divided into 12 rows and 12 columns, presenting the color at full strength at one end to no color at the other. Thus any color reproduced can be specified by one letter and two numbers as: 10C5, which would locate it on Plate 10, Column C, and the fifth color-sample on the vertical scale. The color names are taken from usage in the paint, textile, ceramic, scientific, technical, and artistic fields. A color dictionary is an invaluable aid in the interpretation of color language and serves in addition the very useful purpose of identifying unnamed colorants.

* Published by McGraw-Hill Book Company, New York City.

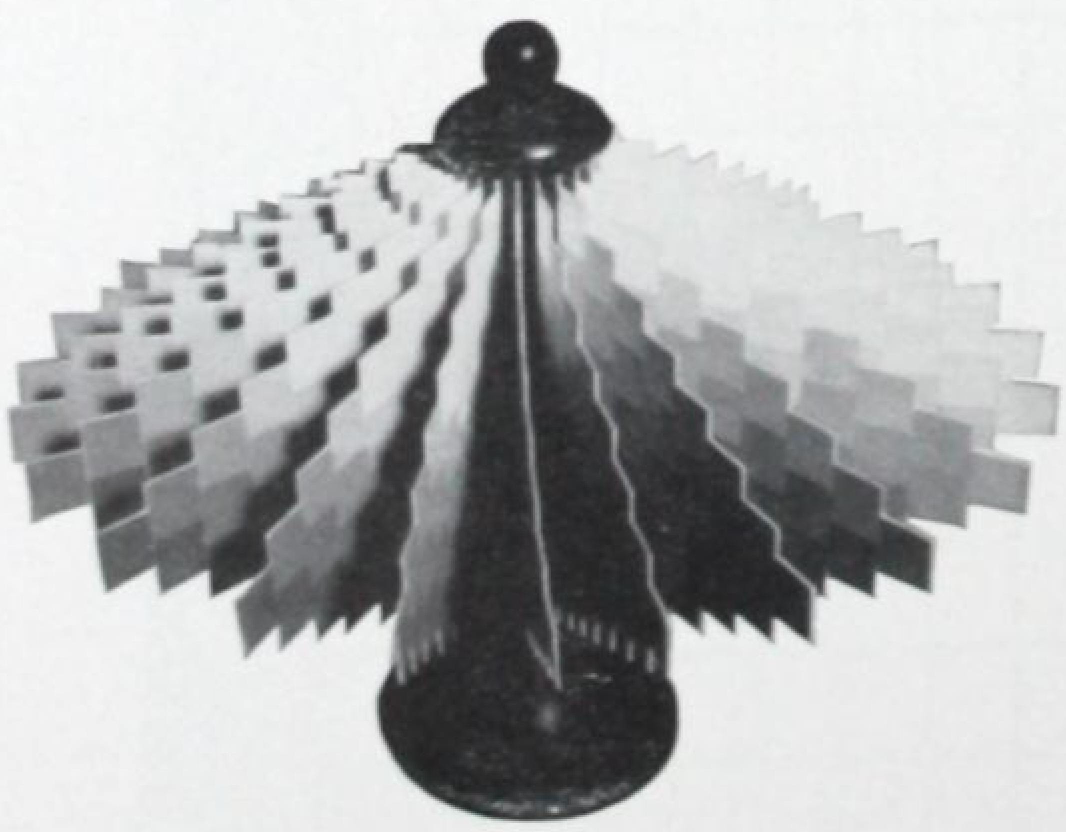
Fig. 80. The Maerz and Paul Dictionary of Color contains 7000 color samples and a list of 4000 color names.



The Munsell Color System

The Munsell Color System also utilizes a set of standards which consist of pigmented or dyed surfaces, printed in the "Munsell Book of Color."* The three variables of *hue, value,* and *chroma* indicate the general divisions of the system. *Hue* indicates the classification of the color by which the eye perceives it as red, orange, etc., as differing from white, black, or neutral grays. *Value* is intended to indicate its lightness or relative brilliance, thus a color may be dark or light red, indicating a position in a light-to-dark scale. *Chroma* indicates the purity of the color or conversely its admixture with white. As white is added to a colorant, its chroma (or saturation) is reduced. When the hue reaches zero and the colorant is all white, the saturation or chroma is zero. This attribute indicates the presence or absence of gray. Substantially uniform scales of each of the three attributes are supplied, with the other two held constant.

Fig. 81. Variables of hue, value, and chroma are illustrated in the Munsell color "tree." Below—Ostwald color "tree"—see page 45.



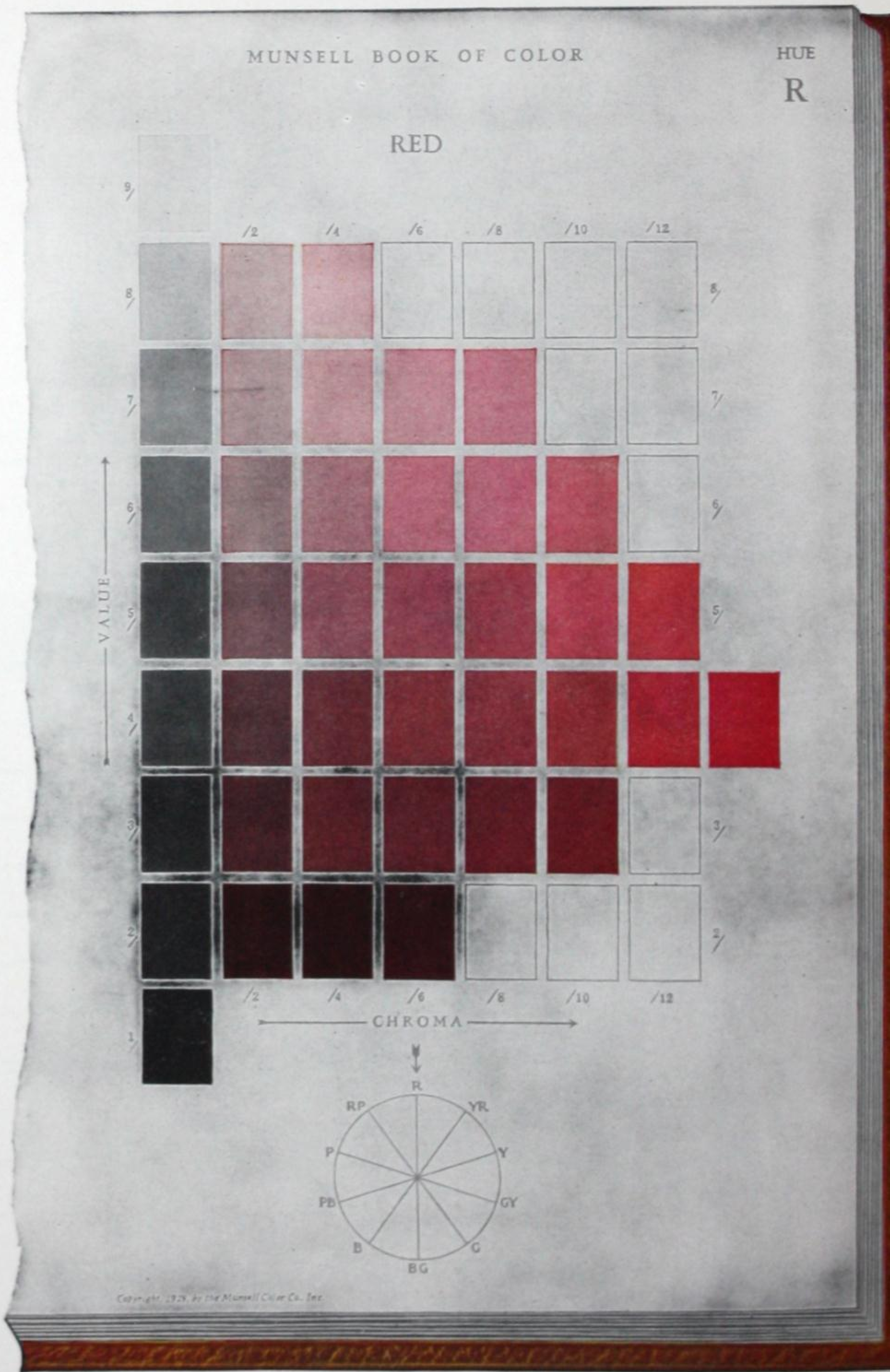


Fig. 82. This page from the Munsell Book of Color shows two of the three variables of the system — **chroma** and **value**. The third factor, **hue,** divides colors as the eye sees them as red, orange, etc.

* Published by Munsell Color Co., Baltimore 20, Md.

The Ostwald Color System

In the Ostwald Color System, surface colors or colorants are divided into (a) *achromatic* colors, such as white, black, and all grays between them; and (b) *chromatic* colors such as yellow, red, blue, green, and all mixtures between them. Chromatic colors are said by the principles of the Ostwald System to be modified in three ways:

1. A yellow may be made redder or greener; a red may be made yellower or bluer; a blue, redder or greener; a green, bluer or yellower. This is called variation in hue.
2. The hue may be retained and increasing amounts of white added. The color then becomes progressively lighter.
3. The hue may be retained and increasing amounts of black added. The color then becomes progressively darker.

A combination of 2 and 3 occurs when the hue is retained and various amounts of gray added. The color then becomes progressively duller.

The system as originally published divided the colors of the spectrum into 100 hues; later publications such as the "Color Harmony Manual"* simplify the presentation to include 24 hues. In this manual a group of 680 "color chips," which are samples of colorants of appropriate color applied to a base of clear plastic, are arranged in a series of 12 handbooks. Each handbook presents two groups of 28 color chips; each group is of a dominant wavelength from the color spectrum and the two groups are approximately complementary to each other. The chips are in a triangular arrangement with eight steps on each side. The apex is the color chip of "fullcolor" (one of the 24 steps) having zero black and zero white content. Two diagonal rows are arranged in steps with progressively more white added to the fullcolor in one and progressively more black added to the other, both by a logarithmic addition. The remaining spaces are in scales of equal-white and equal-black content and in a so-called shadow series whose colors are of equal chromaticity**. The progression is accomplished by adding black to the full color rather than pure pigment. Such a progression from pink, for example, would lead to a soft tone of rose—down to a maroon.

* Published by Container Corporation of America, Chicago, Illinois.
** See Glossary, page 86.

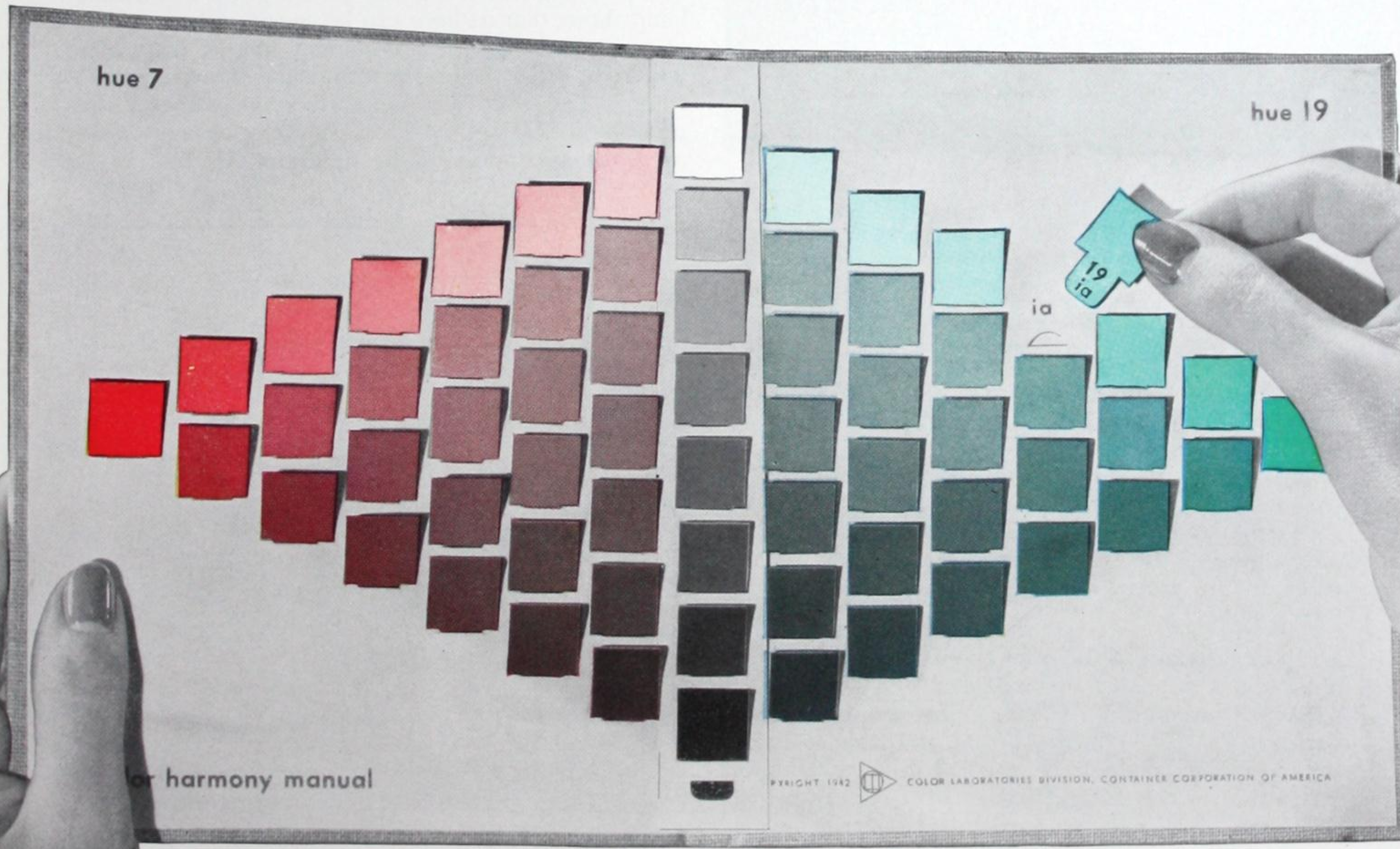


Fig. 83. The Ostwald Color System divides colors into 24 hues (dominant wavelengths). Groups of color chips are arranged in complementary groups in 12 handbooks. A total of 680 plastic color samples is supplied. A later edition includes 943 samples.

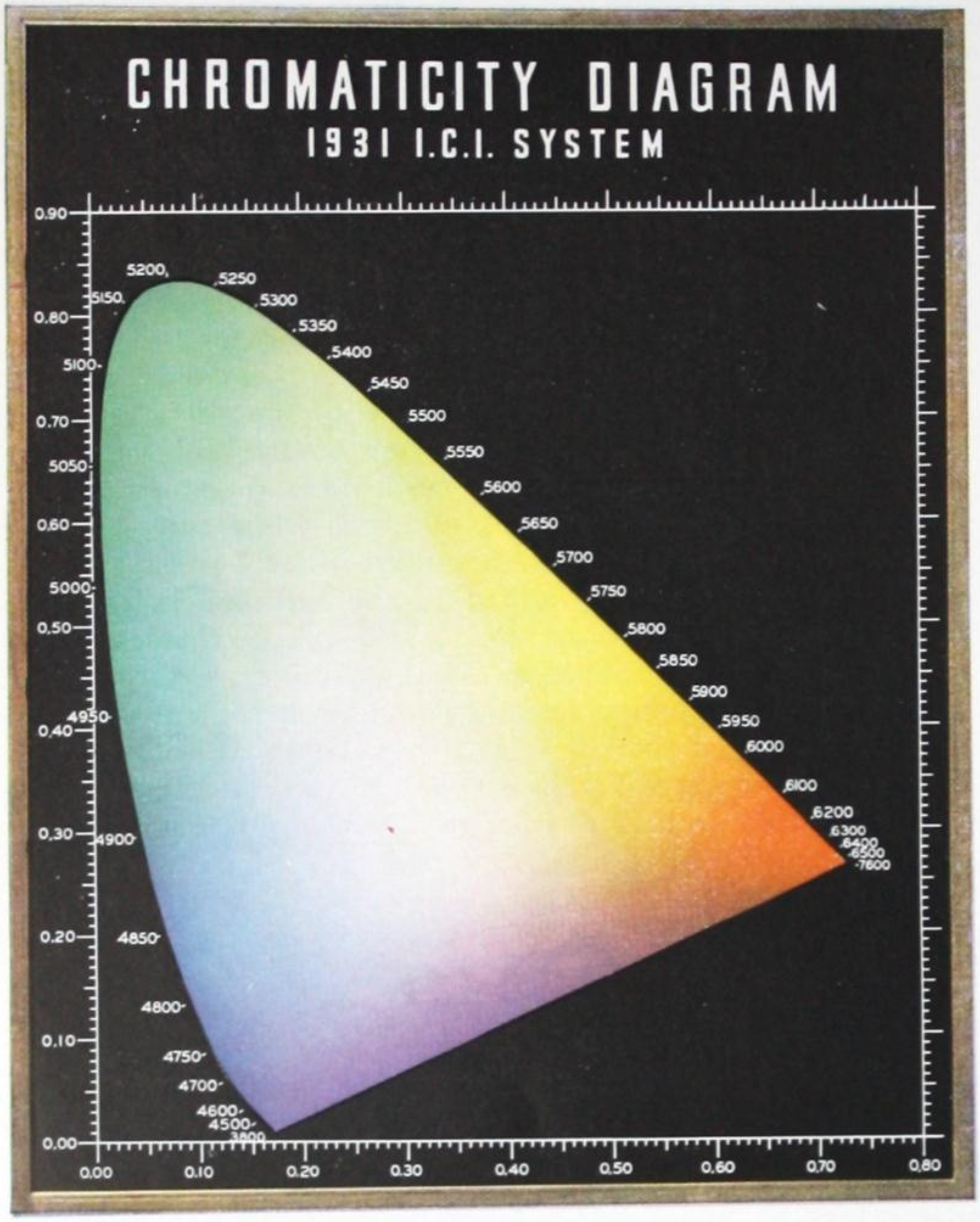


Fig. 84. The I. C. I. Chromaticity Diagram specifies color in terms of theoretical colored lights. With this system all possible colors can be described mathematically.

I.C.I. Chromaticity Diagram

The I.C.I. (International Commission on Illumination) tristimulus method employs a chromaticity diagram (Fig. 84) and specifies color in terms of mixtures of theoretical colored lights. With this system it is possible to coordinate all color systems, and it permits the specification of all possible colors to be shown on one chart. The I.C.I. system of coordinates makes possible the exact specification of colors mathematically by means of only two coordinates on a "color map."

Determination of the color coordinates of a source of light or a colorant is accomplished by a complicated scientific instrument called a spectrophotometer, shown in Fig. 26. This instrument is capable of dividing the visible energy band (Fig. 1) into 10,000 parts and measures the relative energy of a test source in each part. The light reflected or transmitted by the sample is dispersed into a spectrum by means of a quartz prism. Each spectral region is then isolated and the amount of energy in each region is measured by a sensitive cell whose surface is blackened so as to convert the light energy into heat. The relative "weight" of each spectral region is determined in terms of the "standard eye curve" (Fig. 22).

The components of the mixture diagram (Fig. 86) are three theoretical colors of light—reddish purple (X), green (Y), and blue (Z). By means of fixing the "Y" value on the eye-sensitivity curve, a color is translated mathematically by two coordinates, marked horizontally and vertically and plotted as x and y coefficient values (Fig. 86) on the chromaticity diagram

where $x = \dfrac{X}{X + Y + Z}$ and $y = \dfrac{Y}{X + Y + Z}$.

It may be seen that the spectral colors (Fig. 84) lie about the perimeter of the curve; these are the purest or most saturated colors that can be produced. All colors fade into "equal energy white" at the central point. Since all colors are mixtures of spectral wavelengths, all colors lie within the curve and all possible colors can be plotted.

It has been experimentally established that any color may be matched by the addition of suitable proportions of "white" light to some "dominant" wavelength along the spectrum locus (outer curve). As shown in Fig. 85, the point for the green fluorescent lamp shows that its light can be considered a mixture of pure green light (of dominant hue at the wavelength of 5280 Angstroms) and an "Equal-Energy" white. The relative distance from the white to the point representing the green fluorescent lamp indicates the saturation of the light; in this case 58%.

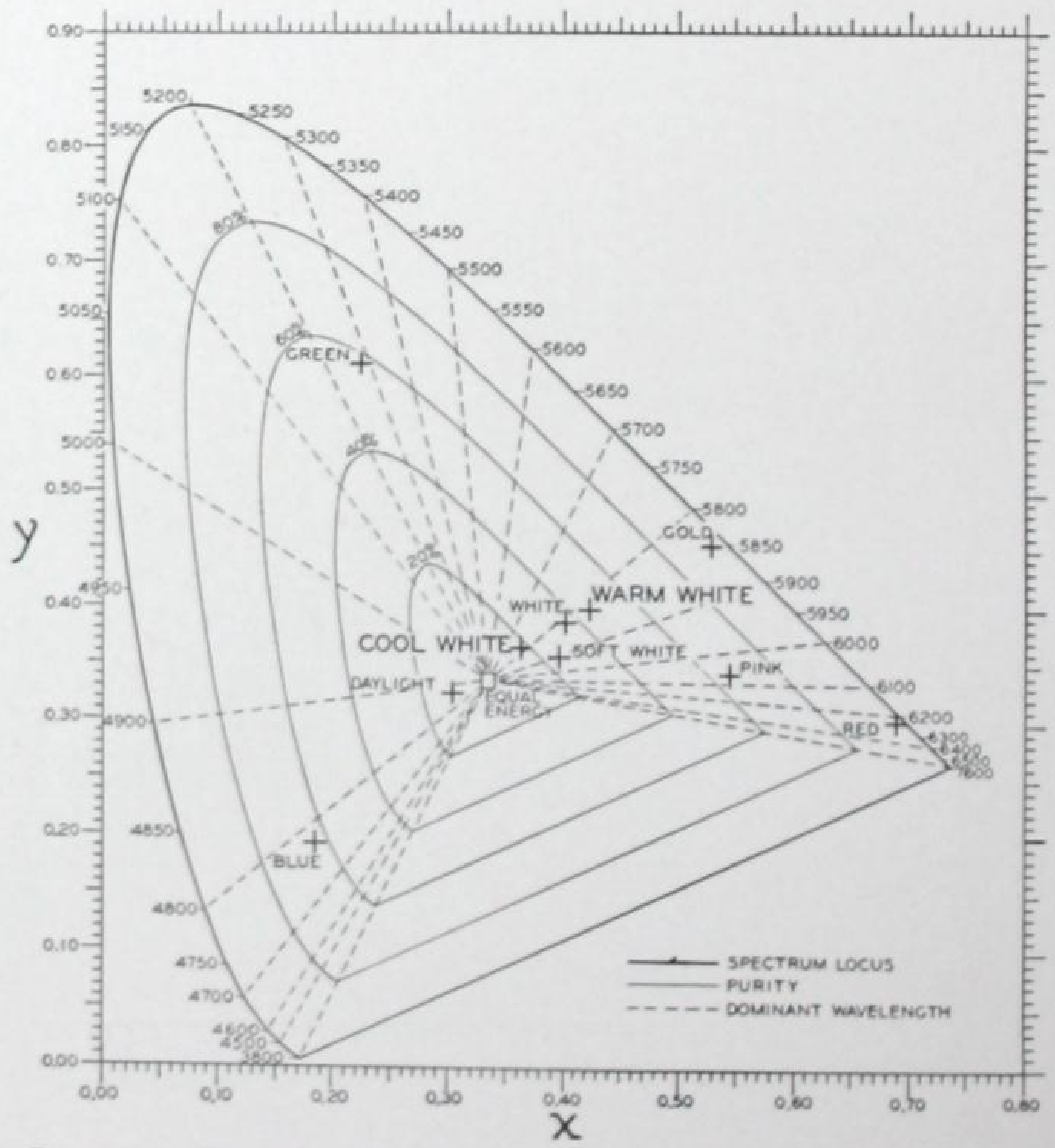


Fig. 85. Chromaticity diagram showing the color locations of filament and fluorescent lamps. The percentage lines indicate per cent saturation or purity.

Color Mixture Nomograph

Any mixture of the light from two colored fluorescent lamps of the same wattage lies along a straight line connecting the two colors on the diagram, the exact point being dependent upon the number of lamps of each color used. A fluorescent lamp color-mixing nomograph is shown in Fig. 86, and indicates resultant colors for various mixtures of fluorescent lamps of present standard color and relative lumen-per-watt output. For example, to determine the color resulting from a mixture of nine blue and three green fluorescent lamps, the numerical ratio of blue to green is 3:1. This ratio is indicated by the figure "3" nearer the blue, on the line joining the blue and green points.

The color resulting from the mixture of three fluorescent lamps is established by the intersection of two construction lines drawn between any two lamp points and the opposite lamp ratio points. For example, the color resulting from a mixture of pink, green, and blue to match cool white is found by drawing a construction line from the blue lamp point through the cool white and marking its intersection with the "green-pink ratio line." This point is noted to be at the ratio of 3.2 pink to 1 green. Then a second construction line is drawn from the pink lamp through the cool white point where it is found

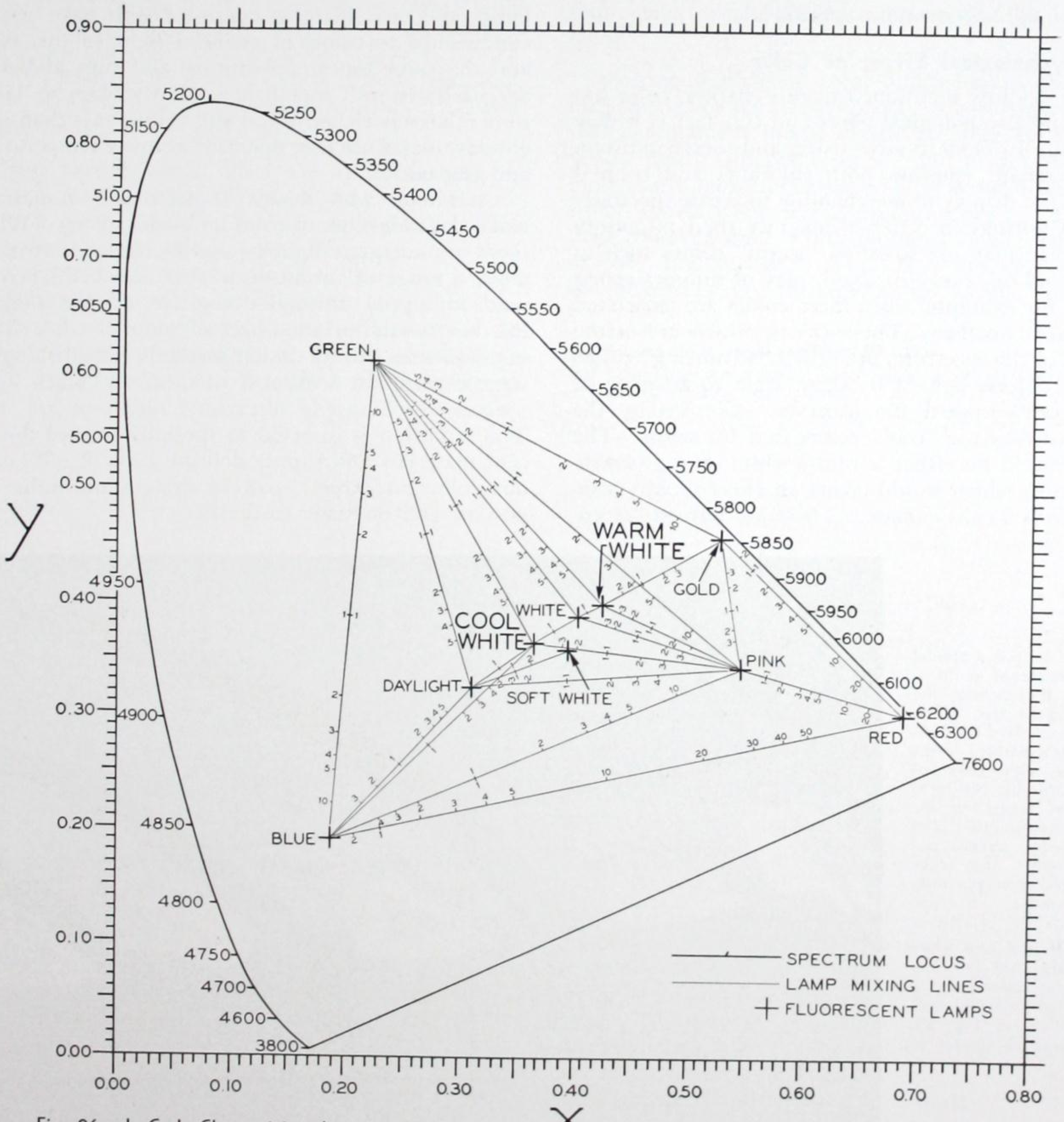


Fig. 86. I. C. I. Chromaticity diagram as a fluorescent lamp color-mixing nomograph.

to intersect the "blue-green" line at the 1 to 1 ratio-point. Hence, a mixture of light from 3.2 pink, 1 green, and 1 blue will produce a color matching the standard cool* white fluorescent lamp.

The color coordinates of filament and fluorescent lamps are shown in Fig. 85. It becomes at once apparent that the familiar filament lamps are actually colored and are surprisingly saturated, relative to the "equal-energy white." There is a definite tendency for these sources to appear "warm" and thus to accentuate reds and yellows when applied to interior illumination. Higher levels of illumination as used today in interiors are usually accompanied by a preference for whiter colors of the illuminant. In other words, as daytime levels are approached, daylight colors of light seem more appropriate.

The Psychological Effect of Color

As previously mentioned in this chapter, color has a powerful psychological effect and this fact is widely put to use in modern advertising and merchandising. The merchant employs both colorants and colored light in the display of merchandise to create spectrally unusual settings in order to magnify their attention-value. He may use so-called "warm" colors such as tints of red or orange in the display of summer sports clothes, for example, since these colors are associated with warm weather. These colors, which are at the red end of the spectrum, are called "advancing" colors because objects lighted by them seem to advance or "stand out" toward the observer. Conversely, the merchant may use "cool" colors in a fur salon. The choice would be either a bluish-white or a greenish-white, tints which would create an effect usually associated with a cold climate. These are termed "receding" colors, since they tend to "move away" from the observer. These terms are applicable both to colorants and colored light. The warm white lamp is an example.

"Warm" colorants for walls and furniture may be similarly selected by a decorator as a means of reducing the "coldness" of rooms with northern exposure, particularly those in which the bluish-white light of the north sky is the principal source of illumination. *Thus a colorant may be selected to balance a color of light or a color of light selected to balance a colorant.*

Colors of Light Sources

It is of interest to note that a large part of the preference for "warm" colors is due to the many years of use of incandescent sources—candles, oil lamps, gas lights, and early filament lamps. People have become conditioned to colors of artificial light in this range and the color tones of furniture and rugs and walls are similarly well established. Early filament lamps were relatively richer in red and yellow rays than present-day ones, since they operated at lower temperatures and efficiencies.

Architects who design theatres and restaurants make the widest use of color and color effects. Where there are adequate lighting and electrical control systems, a range of variations of hue and brilliance are used to supply unusual decorative combinations in the theatre auditorium, often in "mobile" color-changing sequences and by similar methods embellishing the stage-setting. In a number of theatres, "black light" sources which supply ultraviolet radiation are used. The radiation is directed to specially treated fluorescent materials and supply delicate tints of self-luminous color on carpets, pattern designs on walls and posters, and on stage costumes.

Fig. 87. In this Colonial Inn†, fluorescent paint is used for the ceiling, the murals, and the stars. "Black Light" is supplied by 250-watt AH-5 mercury lamps alternated with pairs of 40-watt 360 BL (48-inch) fluorescent lamps in the coves. Red-purple filter glass covers screen out visible light. The room illumination averages one-half footcandle.

* When *de luxe* cool white lamps are used in mixtures, the calculation is made from standard cool white data in Fig. 86. The equivalent number of de luxe lamps is determined by the standard / de luxe lumen ratio.

† Illustration courtesy of The New Jersey Zinc Co.

Color and the Response of the Eye

Besides the factors of pigmentation of objects and the color of the light used on them, there are other factors of significance, which are based on the response characteristics of the eyes of the observer. These are varied in nature; two of them have a unique parallelism in the response of the ear to sound.

Just as some people cannot differentiate certain hues and are "red color-blind" or "green color-blind" (or completely color-blind), some people are tone-deaf to some degree in the high or low tones of the scale. Another pertinent similarity which is a correctable deficiency is known as "color ignorance" by which untrained or indiscriminating persons do not perceive slight color differences at all or are unaware of "clashes" in color combinations. This is equivalent to persons who are said to be "tone ignorant," that is, those who lack training in this phase of musical knowledge.

Other factors which affect the appearance of objects are characteristics of the normal eye. For example, a green object or surface appears bluer on a yellow background than on a neutral gray one. Similarly the same surface appears yellower on a blue background than on a neutral gray surface. Phenomena of this sort are of importance to artists* in the original design of displays and to the illumination system designer who may be called upon to correct the condition with suitable lighting.

Eye fatigue also affects the appearance of objects. The level of illumination upon an object or its brightness greatly affects its appearance generally and invariably its "color impression," particularly when compared with other objects or surfaces which may be adjacent to it. Reflections from clothing, walls, etc., are points which must be frequently considered.

A principle which emphasizes the need for knowledge of both colorants and colored light is evident in the lighting for inspection of colored objects which must be held to narrow color limits**. In these, the color of light should be rich in the spectral region at which the products have maximum absorption (minimum reflectance). This accentuates the difference in color.

For example, small color differences in blue, purple, and violet textiles are most easily detected under tungsten-filament lamps which are rich in red and yellow rays. Differences in red and pink textiles are most easily seen under natural or artificial daylight, which is relatively rich in blue and green. There is little choice in these two illuminants for the inspection of green and yellow textiles. However, there should be radiant energy throughout the visible spectrum.

* Reference—Handbook of Colorimetry by Arthur C. Hardy (The Technology Press, Cambridge, Mass.)

** Lighting to Detect Small Color Differences, A. H. Taylor, (Magazine of LIGHT, No. 7, 1942).

PART VII

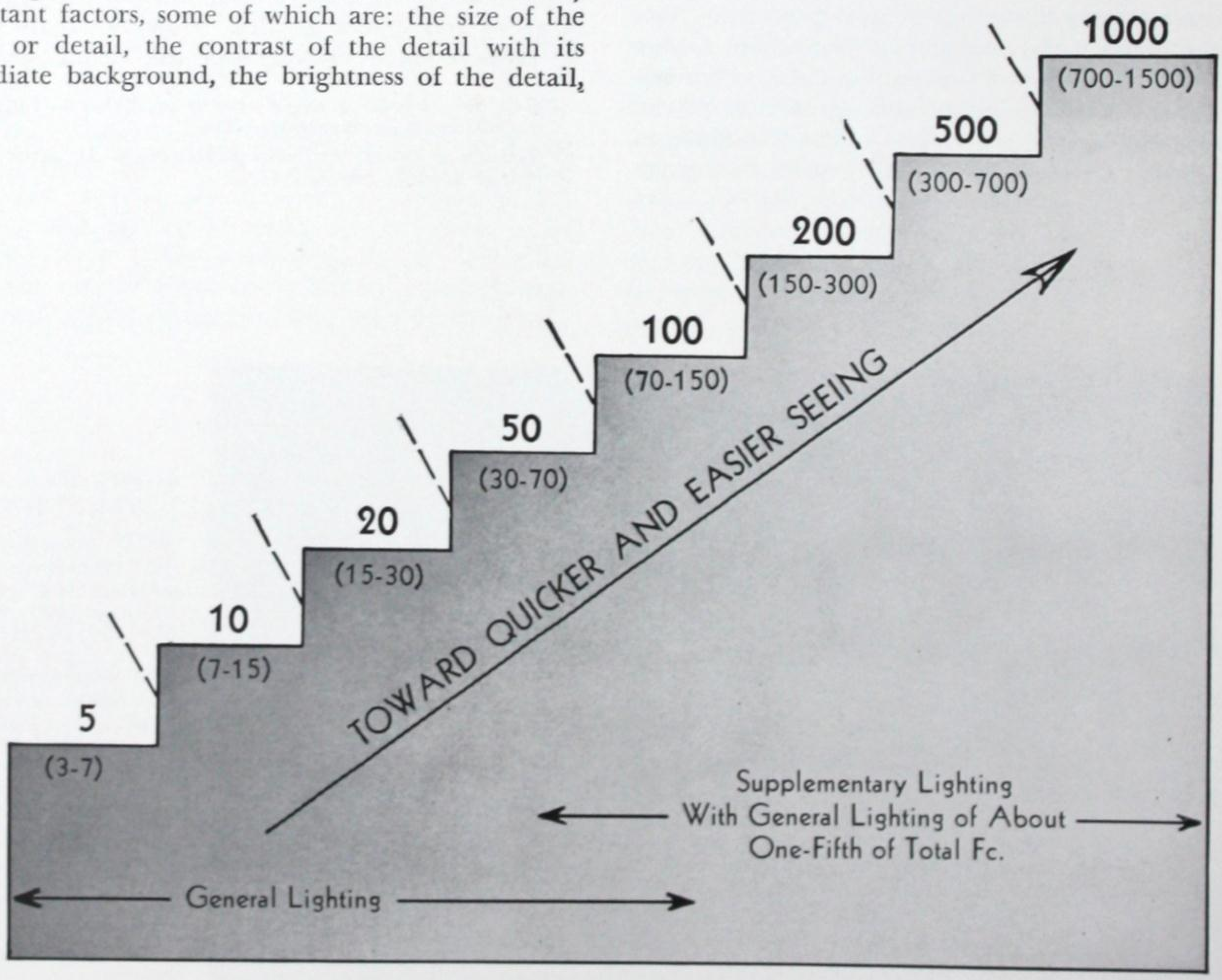
QUANTITY AND QUALITY OF ILLUMINATION

Levels of Illumination

Many considerations are involved in specifying the illumination for various applications. In all cases, the illumination must meet the requirements for such seeing tasks as may be present and in many cases it must also include lighting for esthetic purposes and lighting to attract attention. In meeting these requirements, proper weight must be given such factors as brightness distribution, diffusion, direction, elimination of objectionable shadows, and color quality of the light, as well as footcandles.

Footcandles for Seeing*

Seeing is a function of a number of fundamentally important factors, some of which are: the size of the object or detail, the contrast of the detail with its immediate background, the brightness of the detail, the time available to see it, and the brightness relation between the task† and its surroundings. The desirable levels of illumination to provide good seeing for various tasks can be approached from several viewpoints. For the purpose of this discussion and to help the reader get a better understanding of the problem of specifying footcandles, the different viewpoints are discussed under three premises.



APPROXIMATELY EQUAL STEPS IN FOOTCANDLE EFFECTIVENESS

Fig. 88 — Classification of Footcandle Levels.

* Recommended footcandle levels for specific application are shown in G. E. Lamp Dept. Bulletin, "Levels of Illumination."

† Composed of the detail and its immediate background.

Premise I

Footcandles based on lighting out-of-doors which is free of cost so that, to the extent of its availability, one can always have all he wishes.

If reading of a well-printed book is the seeing task and we take it outdoors at noontime on a clear summer day, we find that a comfortable place to read is in the shade of a building. The sky exposure illumination on the book will vary between rather wide limits—perhaps a range of 100 to 1000 footcandles, depending upon the nearness to the building. Under this range of lighting levels the great majority of people with normal vision would choose something more than 200 footcandles for comfortable reading and when this amount of illumination is readily available, the reader is usually not entirely satisfied with less light. On the other hand, if he moves away from the building and tries to read the book under direct sunshine of 6000 to 8000 footcandles, he will probably conclude that it is too much for comfort, even though this high level lighting is free.

A more difficult seeing job than reading is found in tailoring where the suitmaker must observe dark threads on dark cloth. If this work is done out-of-doors, it becomes distinctly easier to see it under direct sunlight of 6000 to 8000 footcandles than under the lower illumination in the shade of the building; and again, if footcandles were free for the tailor, and the heat were not excessive he would most certainly want the higher levels.

The conclusion to the foregoing is that if one were outdoors on a clear summer day where he could have all the light he might wish, disregarding other factors, he would choose at least 200 footcandles for reading a well-printed book and about 8000 footcandles for sewing dark cloth. Moreover, the 200 and 8000 footcandles desired for these two distinctly different seeing tasks indicate a wide range within which the optimum desirable footcandles will be found for most all the common visual tasks in industrial plants, homes, offices, schools, and stores.

Premise II

Footcandles based on equal visibility for all seeing tasks which must be done when high outdoor lighting levels are not easy to get.

Although 200 or so footcandles are preferred by people with normal vision for reading a well-printed book, this amount of light has been seldom used indoors because conventional artificial lighting methods of the past became obtrusive or unpleasant or presented installation difficulties. By straining the eyes, one can actually see to read with less than a footcandle and experiences have proved that one can read with some ease and comfort with the comparatively low level of only 10 footcandles of illumination; therefore, he often decides to use this amount primarily because it is easy to get. Likewise, if the tailor compromises on about 1/20 of the desired outdoor lighting he will be able to get along fairly well with about 400 footcandles of indoor illumination for his work of sewing dark clothes. In other words, 400 footcandles for the tailor is just as conservative from a visibility and ease of seeing point of view as is 10 footcandles for reading the well-printed book and relative footcandles for most other common visual tasks will be found within the range indicated by these two values.

The relative footcandles for equal visibility become apparent if one looks at the book lighted with 10 footcandles through a pair of goggles fitted with film lenses partially opaqued or slightly diffusing to make the reading matter barely visible at a given distance. Then if these goggles are worn in a workroom

Fig. 89. This visibility meter consists essentially of two circular gradient filters which may be rotated in front of the eyes while looking at any object or actually performing a seeing task. These filters reduce the brightness of the object in the visual field and their slightly diffusing characteristic alters the contrast between the object and its immediate background. Thus, threshold conditions are obtained. The meter has two scales — one of which is calibrated to read relative footcandles and the other, relative visibility. The relative footcandle scale extends from 1 to 1000 and by adjusting the circular filters simultaneously to the threshold of visibility for any object, the scale reading indicates the footcandles required in order that the object will be as visible as 8-point Bodoni type, when both are viewed under standard test conditions. The relative visibility also is read when the object being viewed is reduced to the threshold of visibility. The scale reading obtained in this manner for various seeing tasks represents a range of visibility-levels from 1 to 20 as established with the parallel-bar test standards. For further details see Chapter XII — Light, Vision and Seeing by Matthew Luckiesh — D. Van Nostrand Co., N. Y.

Fig. 90. Visibility test of an office task and a laboratory test of coal lighted by a miner's headlamp.

which is equipped so that the illumination can be adjusted as desired for various seeing jobs, one will be able to observe the footcandles required to make each task barely visible when viewed at the given distance. The footcandle values as observed in this manner will indicate relative illumination levels for all the tasks. The Luckiesh-Moss Visibility Meter, shown in Fig. 89, furnishes such a pair of goggles and a convenient way of adjusting their density so as to reduce the visibility of an object to the point where it can barely be seen. This reduction in visibility is actually accomplished chiefly by reducing the contrast between the details and their background which in turn is due to the veiling effect of a certain amount of scattered light which does not alter the definition of the image. The following list shows approximate values for a few typical footcandle readings with this meter when calibrated for reading 8-point Bodoni type on white paper under 10 footcandles.

5 footcandles—Type of this size on white paper (10-point Bodoni Book)

10 footcandles—Type of this size on white paper (8-point Bodoni Book)

20 footcandles—Good carbon copies of typewritten matter on white paper

30 footcandles—Usual newspaper

50 footcandles—Shorthand notes; also for yellow pages of telephone directory

100 footcandles—Stock quotations in newspaper and for sewing white thread on white cloth

200 footcandles—Fine sanding and finishing of medium reflection factor wood products

400 footcandles—Sewing dark thread and dark cloth

It should be kept in mind that under the foregoing lighting levels none of the tasks can be seen anywhere near as comfortably as out-of-doors where many times the footcandles are available.

Premise III

Footcandles based on present-day practice.

The footcandle values found in present-day practice for various visual tasks are the result of several obvious factors which include the cost of artificial lighting, methods of obtaining it and habits in its use. Furthermore, lighting is always accompanied by a certain amount of heat and radiant energy which in some instances is objectionable and has retarded the approach to desirable illuminations. The more favorable relation of light to radiant heat in the fluorescent lamp is one of the reasons that the newer source led so promptly to the use of higher footcandles and to the conclusion that air-conditioning and proper lighting are economically compatible. Also lighting costs in general have rapidly decreased throughout the years so that today the cost per footcandle is only about one-tenth of that found prior to World War I. Of significance is the fact that during this same period illumination levels have increased about ten times. For example, industrial plants using about 4 footcandles prior to World War I now use 40 footcandles for the same kind of work. In such footcandle increases, however, over a generation, practice has only partially recognized the fact that the more difficult seeing tasks require many times as much light as the less difficult ones. In other words, it is fairly easy to double or triple the 10-footcandle value above referred to for reading, with a result that the use of 30 footcandles or more is good practice in offices. But on the other hand, it is not easy to get the even more needed level of 400 footcandles for tailoring and therefore, in

present-day practice in the tailor shop we are more likely to find 50 to 100 footcandles with a maximum of about 200. Likewise, for most all the more difficult seeing tasks, the footcandle values in practice as listed in the table indicate such comparatively low levels that these tasks become relatively more difficult than reading under even 10 footcandles. This, of course, penalizes those people who have the more difficult jobs to perform. Also it should be mentioned that present-day practices impose a handicap on the many people having subnormal vision and most of those in the older-age groups. These people are especially penalized because they require more light to do the same visual work.

Footcandles for Selling

Whether it be goods or services that are sold, lighting is a prime element in the three factors of merchandising: attraction, atmosphere, appraisal. Each of these factors plays a part in the success of a store or a gas station, and even in that of a theatre or other place of amusement.

A pattern of brightness must be depended upon to capture the *attention* and interest of potential customers passing rapidly in vehicles or afoot, so that they will want to come into the place of business. Inside, as well, the distribution of brightness affects their movements, determines what they look at, influences the numbers and kinds of things they buy and how often they return. Thus, the desirable illumination is governed by more than the requirements of particular seeing tasks presented by the merchandise; it has to do with such factors as competition for the consumer's dollar, with turnover or sales per square foot, and with realizing the greatest return from investment in other appointments.

Higher values of illumination more fully reveal color, pattern, texture, workmanship, subtleties of styling, inherent quality. Quick, accurate *appraisal* brings quicker decisions, speeds sales. Light of appropriate amount and color quality radically reduces returns. Dark goods, fine detail, and items of high intrinsic value usually need more light than those of high reflection factor and plainer character.

The store to which people like to return again and again uses light to create an *atmosphere* of alertness and cheerfulness, to add accents of interest, and by coordinating the newly available tints and colors of the fluorescent lamps with the store decoration to create a mood which is characteristic and appealing.

The classifications that follow indicate footcandle values found desirable in the experience of successful business institutions. Each step upward in the footcandle scale is about twice that of the preceding one. This is the minimum difference which is significant from the standpoint of attention value. Greater differentiations in brightness and variations in color will be found progressively more potent. Thus featured displays take a relativly high classification, as do show windows which must command attention from rapidly moving eyes and convey their story in a few seconds.

Present-day Footcandle Values

It has been known for many years that the contribution of footcandles toward effectiveness in seeing is represented by a geometric scale approximately 5, 10, 20, 50, 100, 200, 500, 1000, etc., footcandles and not by arithmetical steps such as 1, 2, 3, 4, etc. This is illustrated diagrammatically in Fig. 88. In this chart the 100 step is about 10 per cent of outdoor illumination on a heavily overcast day. For a significant improvement above "100" toward quicker and easier seeing, it is necessary to advance to "200" and so on. Typical present-day practices in applying these footcandle classifications to various seeing tasks are given in the following paragraphs. As discussed above, the more difficult seeing tasks are not usually as well lighted from the standpoint of the detail to be seen, as are the less difficult ones. Those tasks which at present are most neglected in this respect are marked with an asterisk (*).

Footcandle Classification—100 (70 to 150)

For very exacting and prolonged seeing tasks such as fine bench and machine work*, extra fine hand painting and finishing, and for the discrimination of fine detail of low contrast as in pressing dark cloth products and drawing dark woolens*. For showcases, wall cases, and open counter displays in stores where discrimination of detail and attention value are important factors.

Footcandle Classification—50 (30 to 70)

For severe and prolonged seeing tasks such as medium bench and machine work, medium fine assembly and inspection*, prolonged reading and studying, drafting*, printing press work, office work such as bookkeeping, typing, accounting, and children's (home) studying*. For general merchandising areas in stores and for exhibition games in gymnasiums.

Footcandle Classification—20 (15 to 30)

For moderately critical and prolonged seeing tasks such as rough bench and machine work, rough assembly and inspection, casual reading and writing, hand painting and finishing, for pressing light colored leather products, and weaving light colored rayons. For circulation areas in stores.

* Tasks commonly neglected from a lighting adequacy standpoint.

Footcandle Classification—10 (7 to 15)

For visually controlled work in which seeing is important but more or less interrupted or casual, and does not involve discrimination of fine details or low contrasts—for rough work, such as breaking and screening coal, glass-blowing machines, billet, blooming, and sheet bar mills in steel manufacturing. For stock rooms and active storage areas for a variety of small articles such as for merchandise stocks.

Footcandle Classification—5 (3 to 7)

For interiors where crude manual tasks are intermittently carried on, such as required for grinding clay products and cements, stone crushing, hand furnaces and boiling tanks in chemical plants, stock rooms and active storage areas for bulky materials; for the safe movement of people through corridors. For active work areas out-of-doors—loading docks and quarries.

Footcandle Classification—200 (150 to 300)

For extra fine inspection such as required in making jewelry* and precision instruments*, sewing*, and inspection of dark leather products. For basic lighting of show windows in main business areas and for feature displays in show windows in secondary business areas; for featured merchandise in the store.

Footcandle Classification—500 (300 to 700)

For inspecting dark cloth products, for color television studios, and accent lighting in show windows in main business districts.

Footcandle Classification—1000 (700 to 1500)

For featured displays and for daytime illumination in show windows; for hospital operating rooms.

* Tasks commonly neglected from a lighting adequacy standpoint.

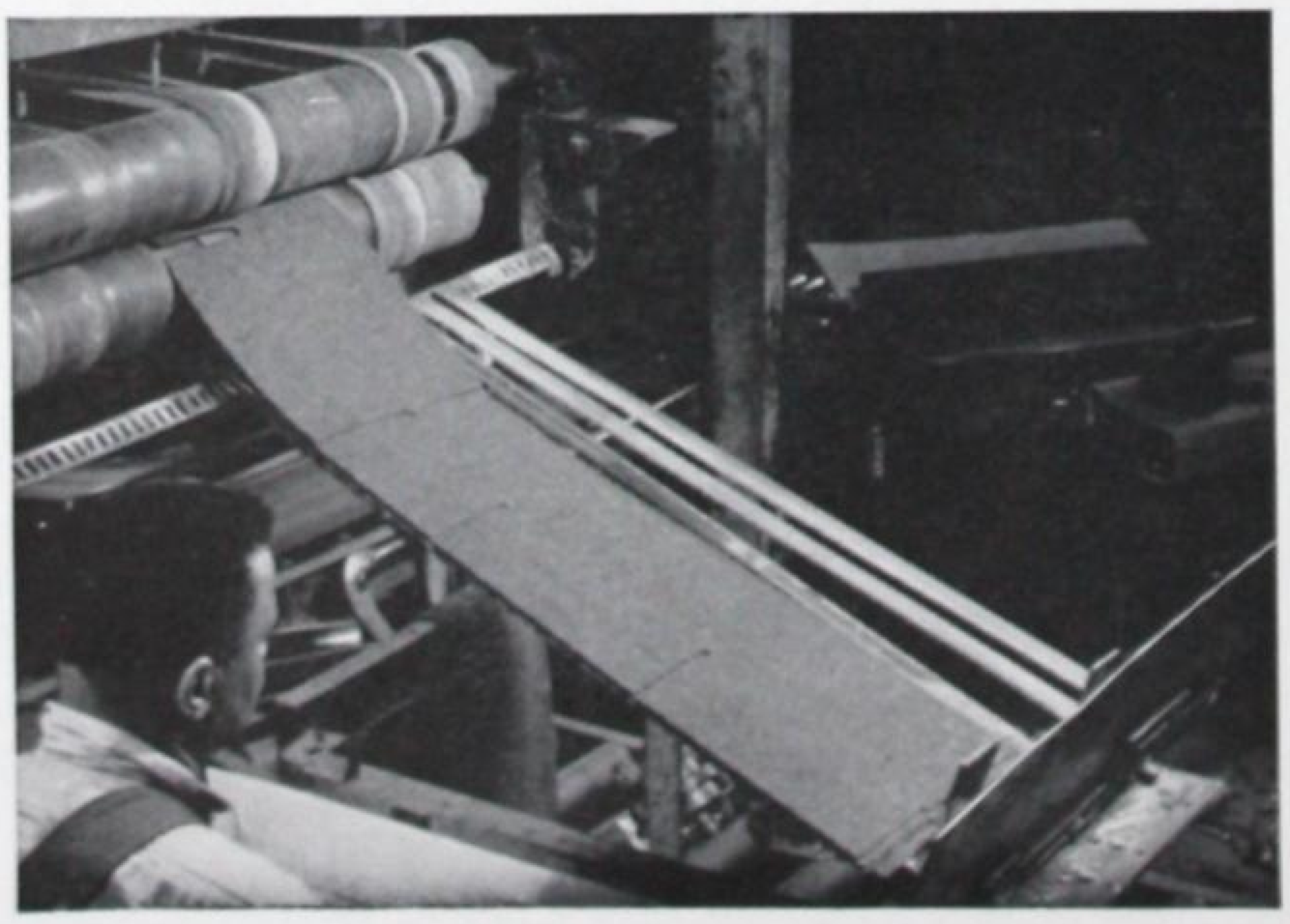
Supplementary Lighting

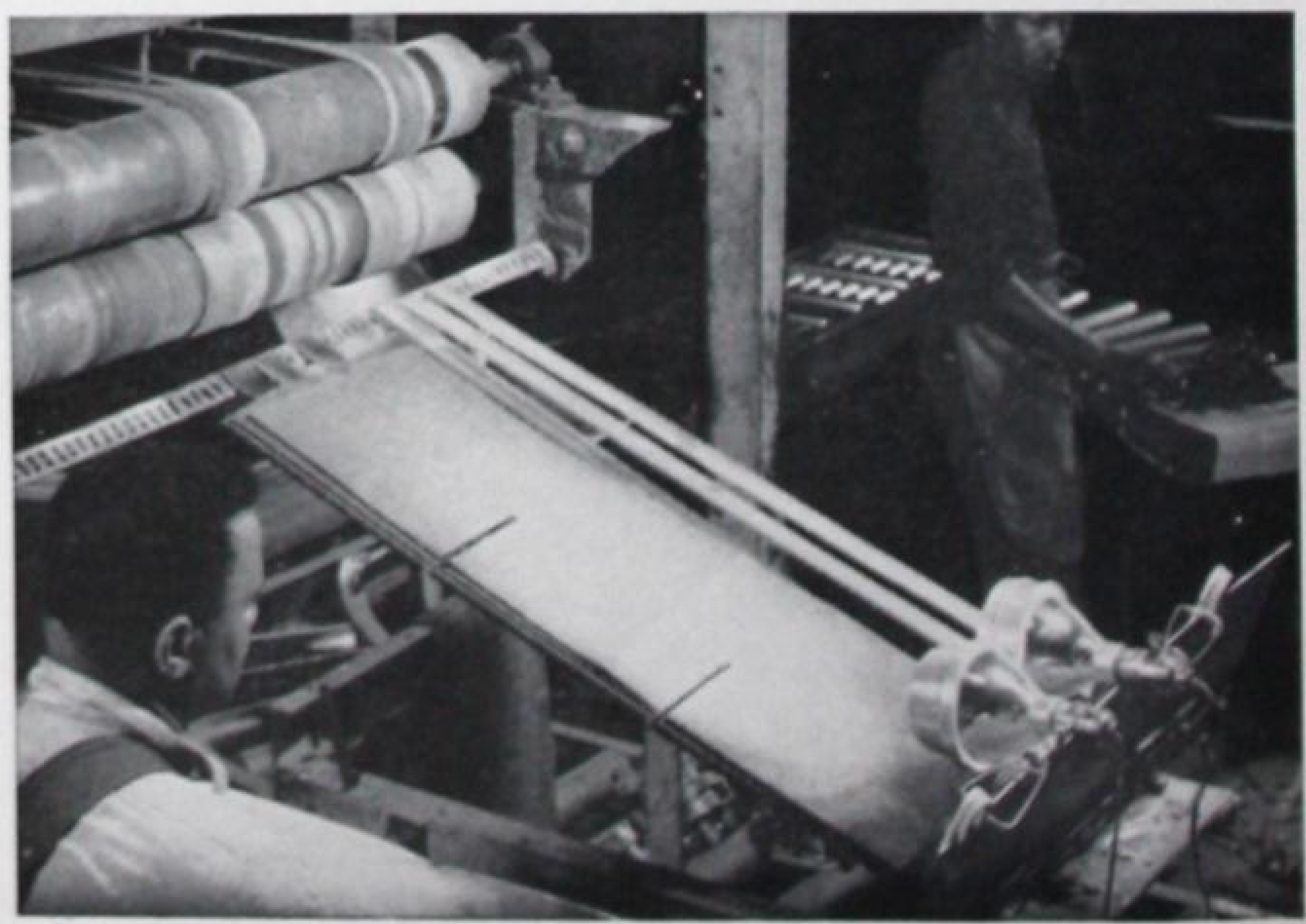
In those cases where the higher footcandle values are required for the more difficult seeing tasks in work places; and for many home lighting applications it is often practical, economical, and desirable to instali supplementary lighting equipments. Supplementary lighting, as the name implies, should be used in conjunction with the general lighting system and when the combination is used for prolonged close work it should be planned to avoid too great a brightness ratio between the work areas and the surroundings. This is usually accomplished when the general lighting system provides illumination of the order of ⅓ to ⅕ the total footcandles. In merchandising displays a greater range is permissible in order to obtain maximum attention value. On the other hand, a difference greater than about 2 to 1 between the illumination in a showcase and on the counter-top may result in a less favorable appearance of goods when brought out for examination.

SHADOWS

For satisfactory seeing, lighting with a certain amount of shadow is often necessary. Shadows give form to objects, for example, it is possible to distinguish between a circular disk and a sphere of the same diameter by a gradation of shadow on the sphere and the absence of it on the disk. Or for the inspection of rough-surfaced materials such as roofing paper or shingle-strips, it is often necessary to install supplementary lighting units so that short, sharp shadows are present to reveal details or faults in the material (Fig. 91). These have been termed "useful shadows."

Fig. 91. Satisfactory seeing is supplied on this asphalt shingle inspection table with the projector lamps (right). They improve the brightness and add shadows of the particles of stone, revealing details not visible with diffuse lighting (left).
▼





Sharp, black shadows often make objects appear harsh and when such shadows hide parts of machinery, as in an industrial plant, they may become extremely dangerous. Similarly, if the aisles are darkened by shadows of stacks of material or other obstructions, the dark areas are potential sources of accident, due to workmen tripping over objects which may be left on the floor. The sharpness of shadows is usually a function of the type of luminaire; the more direct the light from it, the sharper and blacker the shadows. When the lighting units are installed too far apart, the shadows they cast of machinery and other objects are long and correspondingly dangerous. Luminaires properly spaced decrease this hazard, the shadows are wiped out by the overlapping distribution of light or are illuminated sufficiently.

The study of the modulation of light and shade is an important phase of illuminating engineering, especially from an artistic standpoint. It is paramount in photography, and in a more permanent form, it is most vital in the illumination of sculpture.

Highlights and shadows on a sculptured bust, for example, can greatly modify the expression of the face and conceal or reveal details which may make or mar its beauty. An idea of the change which can be wrought in the appearance of a piece of sculpture may be seen in Fig. 93. In the right-hand illustration, a fine handling of highlight and shadow, the effect is of repose and grandeur, and the beauty and excellence of this masterpiece of Italian Renaissance art are emphasized.

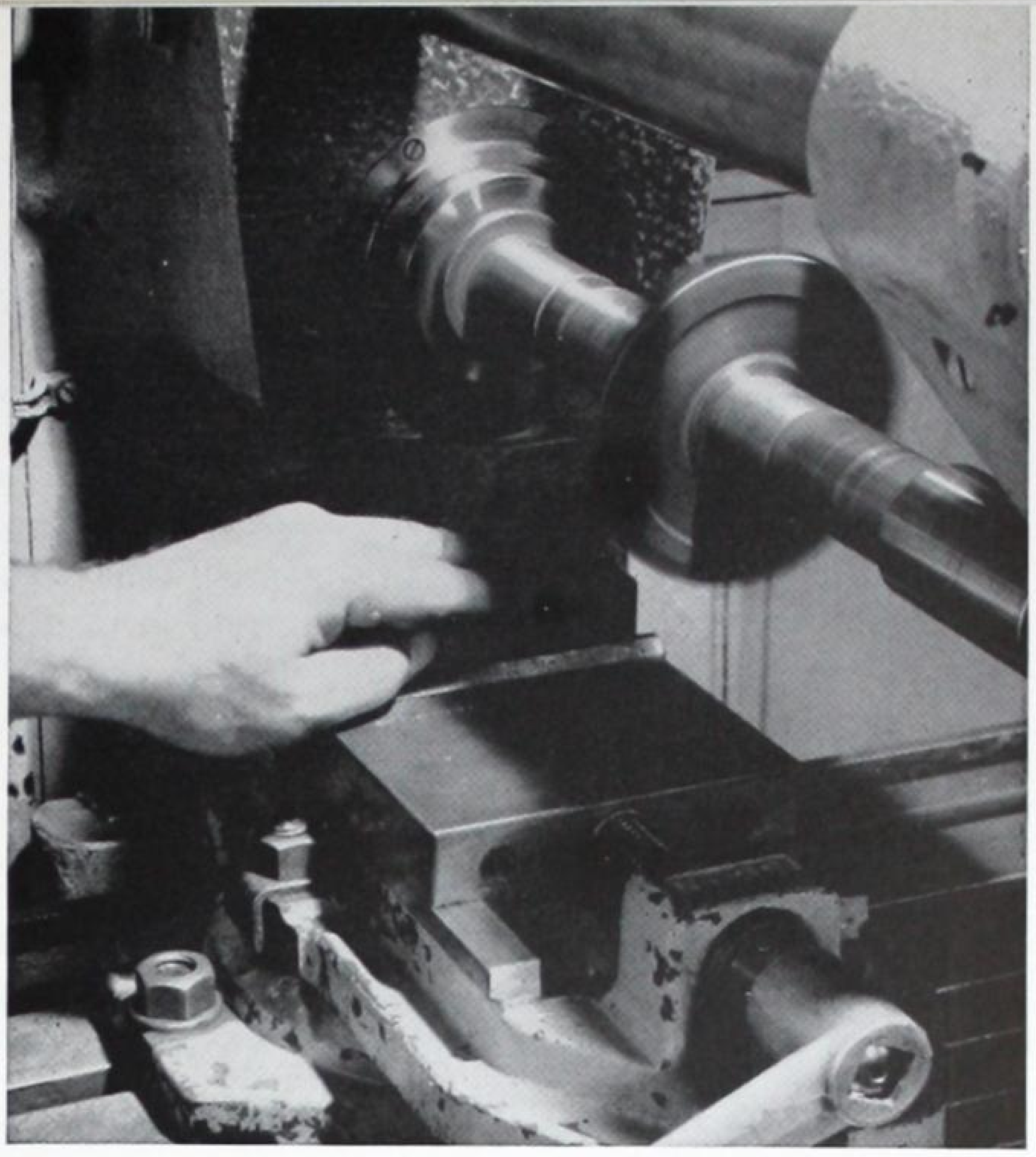


Fig. 92. Sharp, black shadows cast by glaring lamps are dangerous in industrial interiors.

The left-hand illustration seems scarcely recognizable as the same work. The sharp shadows cause the eyes to bulge and the dark background sharpens the outline of the head and shoulders disproportionately. The emphasis of highlights draws the viewer's attention to the details of dress; the repose and beauty of the face are completely lost.

In lighting this example of sculpture the final specification effected a type of lighting similar to that from the sun against a slightly overcast sky. The

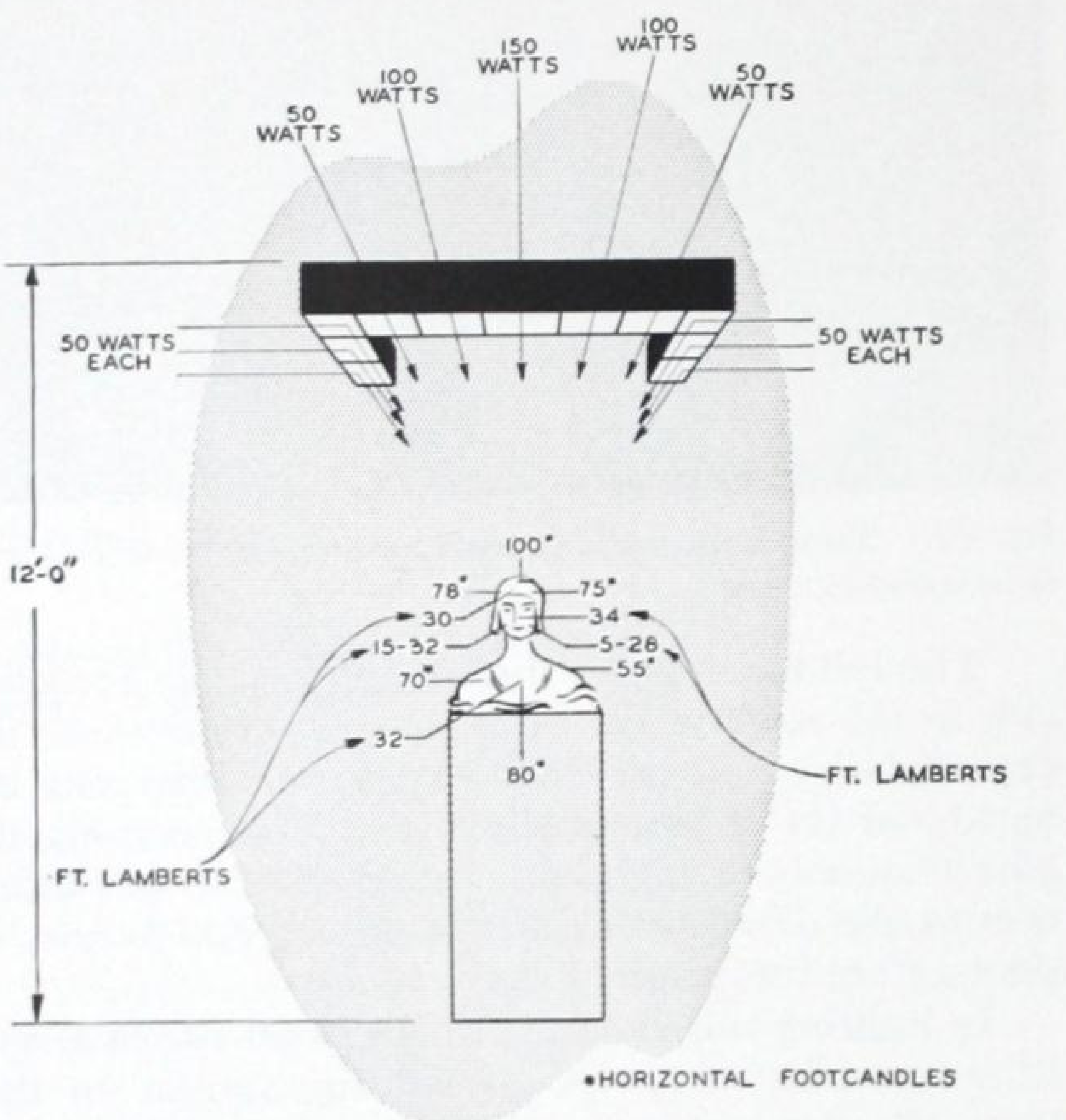
Fig. 93. These two views of the same sculptured bust, show the importance of correct illumination to preserve the expression and beauty intended by the sculptor.

dominant beam was obtained by a 150-watt concentrated filament lamp in a luminaire, containing a reflector and lens-plate. Eight 50-watt units as shown in Fig. 94 supplied the remainder of the lighting pattern.

The use of comparable analytical technique* is of importance in commercial establishments. Shadows are a definite part of the lighting composition of display niches, furniture groups, and show window ensembles, and lend dramatic emphasis to important parts of each display. Sources such as colored reflector and fluorescent lamps, projectors containing roundels, and similar equipment add color, color fringes or colored shadows. The value of "painting with light" in this manner has been demonstrated to be of vital importance from a decorative viewpoint.

In drafting rooms, the presence of shadows at the edges of triangles and T-squares causes difficulty in seeing of important details and results in eye fatigue. Since a high percentage of drafting work is done with horizontal and vertical lines, experience has indicated that if the drafting tables are turned at an angle of 45° with respect to the rows of units, the shadows along the edges of the T-square and triangles are practically eliminated.

The same quality of lighting can be obtained by installing the units in diagonal rows across the room, with the tables in conventional position.



◀ Fig. 94. Diagram of installation for right-hand view of Fig. 92. The arrows indicate the dominant direction.

* Ref. Modeling with Light, H. Logan, Illuminating Engineering, Vol. 36, p. 202.

Fig. 95 (Left) Line shadows may result from having drafting tables parallel to semi-direct fluorescent luminaires. By aligning the tables so that they are at an angle with the luminaires, the shadows from triangles and T-squares can be lessened considerably.

Fig. 95 (Right) Best drafting practice includes the use of vertical boards with drafting machines or counter-balanced straight-edges. Shadows and reflected glare are minimized or eliminated. Better posture and more economical space utilization are additional advantages.

▼

GLARE

Glare has been defined as "light out of place." It is any brightness within the field of view of such a character as to cause discomfort, annoyance, interference with vision, or eye fatigue. Glare reduces the sensitivity of the visual sense, and therefore reduces the visibility of an object or seeing task. Glare is distracting and annoying often to the extent of causing extreme discomfort and even pain.

The principal causes of glare include:

1. Light sources of high brightness.
2. Lack of adaptation.
3. Excessive candlepower (volume of light in the direction of the eye.
4. Location of exposed light sources near the line of vision.
5. High brightness contrasts between the object and its surroundings.
6. Prolonged time of exposure to the glare-source.

During the period of industry development when the filament lamp was the only source used for general lighting, indirect lighting systems produced the least glare. They were limited, however, to a maximum of 50 footcandles; beyond this, the ceiling brightnesses became so high that they were sources of discomfort-glare.

Discomfort-Glare Appraisal Systems

When the fluorescent lamp was introduced in 1938, some luminaire designers felt that because fluorescent lamps were so much less bright than filament lamps, complete concealment of them was not necessary. However, the large number of tubes needed to obtain required footcandle levels meant that the total luminous area in rooms become quite large. Actually, fluorescent lamp and luminaire brightnesses were of the same order as white-glass enclosing globes, so popular in the days of 10 to 20 footcandles. In offices and schools where poorly-shielded fluorescent luminaires were used, the occupants began to complain, and the expressions "too much light" or "something's wrong with fluorescent lights" were heard. However, the real difficulty was discomfort glare.

The immediate need was to establish the fact that luminous area is important as well as brightness. A method of rating room-lighting systems for discomfort due to direct glare was introduced in 1945 by Ward Harrison*. The method, based on experience and data available from past researches, evaluated the effects of source area and brightness, the nature of the surroundings, and the position of the light sources. The numerical "glare factor" expressed the visual discomfort caused by the luminaires in a specific interior.

* "Glare Ratings," Illuminating Engineering, September, 1945; "Further Data on Glare Rating," Ward Harrison & Phelps Meaker, I.E., Feb., 1947.

Thus it was an index of the suitability of the lighting system for the grade of work being done. It is computed by the following empirical equation, applied to each luminous source; the answers are added to obtain the final factor:

$$\text{Glare factor} = \frac{\text{Source Area x Brightness}^2 \text{ x Location Coeff.}}{(\text{Height Above Eye Level})^2 \text{ x Surround Factor}}$$

Published glare-factor tables of typical installations† have proved the usefulness of the system. They have enabled designers to avoid serious mistakes in interiors where critical tasks are performed.

Laboratory researches which have contributed to the accuracy of the glare-factor equation have been published by Drs. M. Luckiesh and S. K. Guth‡. In these, observers identified their sensations under certain visual conditions as the Borderline between Comfort and Discomfort, called BCD. The studies established the relationships between brightness, area, and position of luminaires, and eye adaptation.

Fig. 96 illustrates one of the basic BCD researches. All other factors being fixed, observers adjusted the brightness of a source until the "glare sensation" was at the BCD point. The center point c in Fig. 96, where half the observers are visually comfortable, corresponds to 100% BCD brightness by definition. The curve shows two things: 1. the wide variation in sensitivity to brightness between individuals, and 2. the relation between brightness and the percentage of visually comfortable persons. It will be noted that at "a" approximately 2% of the observers are visually comfortable at a luminaire brightness 1.8 times the BCD value. On the other hand, at "b" 95% find a brightness 40% of BCD to be visually comfortable.

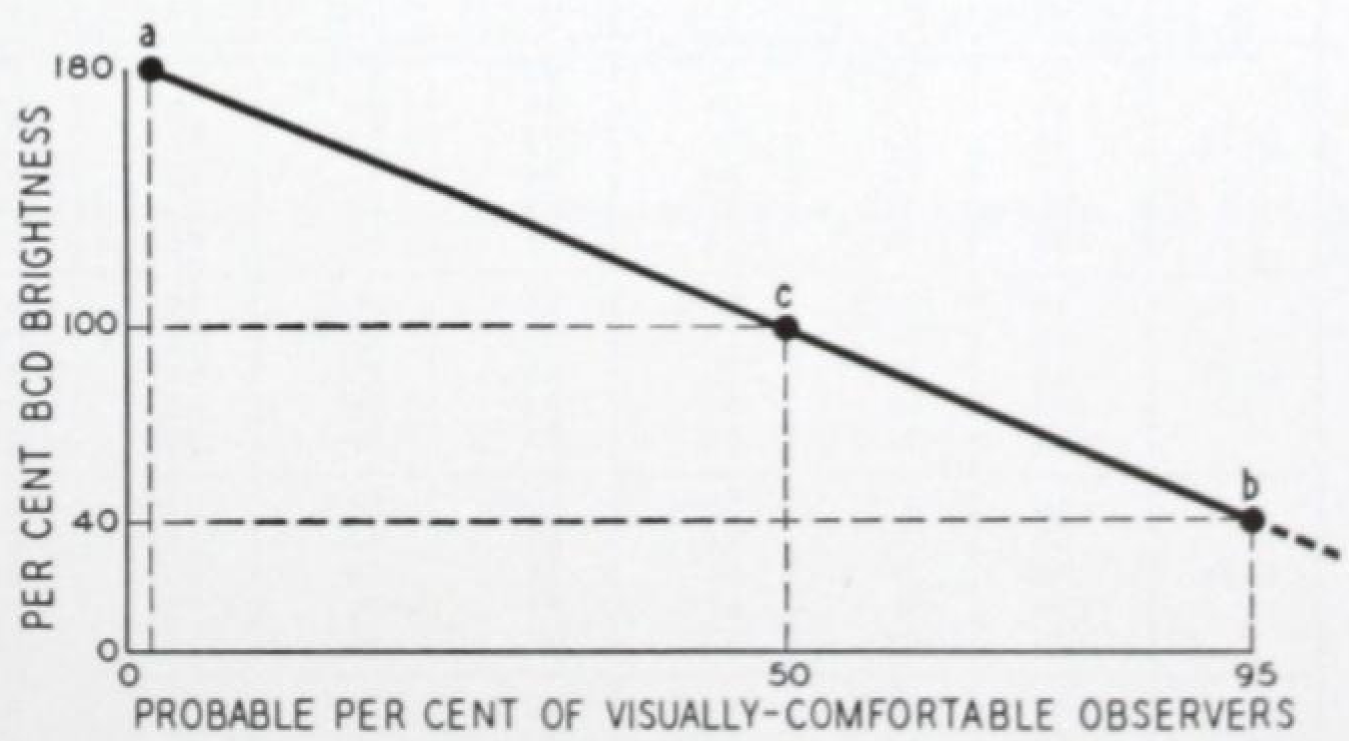


Fig. 96. This basic BCD research shows the relation between brightness and the probable percentage of observers visually comfortable in the least desirable position in a typical room (see text). All factors except luminaire brightness are fixed.

† "Glare Factors and Their Significance," G. E. Review, August, 1947.
‡ "Brightnesses in Visual Field at Borderline Between Comfort and Discomfort (BCD)," M. Luckiesh and S. K. Guth, I.E., Nov., 1949, and "Comfortable Brightness Relationships for Critical and Casual Seeing," I.E., Feb., 1951; "BCD Brightness Ratings in Lighting Practice," I.E., April 1, 1952, S. K. Guth.

Significant improvement in comfort rating of a lighting system can be made by reducing luminaire brightness. Where lamps are exposed to view, a 45% reduction in brightness can be had, for example, by changing the luminaire specification from one using 40-watt T-12 fluorescent lamps (1900 fL) to one using 40-watt T-17 (1050 fL) lamps. Changes in shielding and density of diffusing glass or plastic are also effective in raising the percentage of visually-comfortable persons in a room.

By combining glare factors and BCD findings, tables of Visual Comfort Indexes such as are shown below have been developed. These tables express the approximate percentage of occupants who would be visually comfortable in each room, were they to be seated in the least favorable position. This is assumed to be at the center of one end of the room with the seated person facing the opposite end of the room. All persons are assumed to face in this direction.

The two tables give results for rooms lighted by typical luminaires of widely different design. From the tables it will be observed that rooms vary widely in visual discomfort. The longer or larger the room the greater the number of luminaires which may cause visual discomfort. For example, according to the Luminaire B table, a room 20 ft. x 20 ft. with a 16-ft. ceiling has a 72% rating. A similar room 100 ft. long has a rating of only 17%.

VISUAL COMFORT INDEX — 50-FOOTCANDLE LIGHTING SYSTEMS

LUMINAIRE A: A two-lamp (40-watt T-12) fluorescent luminaire having diffusing-glass sides, open top, and bottom louvers with shielding 35° crosswise and 25° lengthwise. Luminaires are suspended not less than 18 inches from the ceiling. Room surfaces: Ceiling — 75% R. F.; Walls — 50%. A 50-footcandle (maintained) installation using this luminaire will be visually comfortable to approximately the percentage of occupants indicated when in the worst position in the room.

Luminaire A		Height Above Floor							
		8½ ft.		10 ft.		13 ft.		16 ft.	
		Viewing Luminaires		Viewing Luminaires		Viewing Luminaires		Viewing Luminaires	
ROOM Width	ROOM Length	Length-wise	Cross-wise	Length-wise	Cross-wise	Length-wise	Cross-wise	Length-wise	Cross-wise
15 ft.	20	94%	91%	95%	94%	97%	97%	94% and higher	
	30	93	88	95	92	96	96		
	40	93	86	95	90	95	94		
	60	93	83	95	88	95	92		
	80	93	81	95	86	95	91		
20 ft.	20	93%	90%	94%	93%	96%	97%	97%	97%
	30	93	86	94	90	95	95	96	96
	40	93	85	94	88	95	93	96	96
	60	93	80	94	85	95	91	95	93
	80	93	77	94	84	95	90	95	93
	100	93	74	94	82	95	89	95	92
30 ft.	40	92%	82%	93%	86%	94%	92%	95%	94%
	60	91	76	93	82	94	89	95	92
	80	91	70	93	79	94	87	95	90
	100	91	67	93	76	94	84	95	90
	150	91	64	93	70	94	82	95	87
40 ft.	40	91%	80%	92%	86%	94%	91%	95%	94%
	60	90	74	92	80	93	87	94	91
	80	90	66	92	76	93	84	94	89
	100	90	62	91	71	93	83	94	87
	150	89	58	91	66	93	78	94	85
60 ft.	60	88%	69%	90%	78%	93%	85%	93%	90%
	80	87	63	90	72	92	83	93	87
	100	87	58	89	67	92	79	93	85
	150	86	51	89	59	91	71	93	80

LUMINAIRE B: A recessed shallow two-lamp (40-watt T-12) white fluorescent troffer, bottom covered with diffusing glass, flush with ceiling. Room surfaces: Ceiling—75% R. F.; Walls—50%. A 50-footcandle (maintained) installation using this luminaire will be visually comfortable to approximately the percentage of occupants indicated when in the worst position in the room (see text). The orientation of these luminaires (lengthwise vs crosswise) makes no substantial difference in comfort.

Luminaire B		Height Above Floor			
ROOM Width	ROOM Length	8½ ft.	10 ft.	13 ft.	16 ft.
15 ft.	20	8%	19%	52%	
	30	6	11	30	
	40	*	9	22	
	60	*	8	18	
	80	*	7	16	
20 ft.	20	7%	14%	47%	72%
	30	*	7	23	45
	40	*	6	16	30
	60	*	*	12	21
	80	*	*	11	18
	100	*	*	10	17
30 ft.	40	*	*	10%	20%
	60	*	*	6	12
	80	*	*	*	10
	100	*	*	*	9
	150	*	*	*	8
40 ft.	40	*	*	8%	15%
	60	*	*	*	8
	80	*	*	*	6
	100	*	*	*	6
	150	*	*	*	*
60 ft.	60	*	*	*	6%
	80	*	*	*	*
	100	*	*	*	*

* Probably not over 5%.

These ratings and those for similar rooms 40, 60, and 80 ft. long are shown in Fig. 97b. They indicate that the visual comfort of a person in a large room improves as he moves toward the front wall, and in Fig. 97a show the relative number of luminaires in view.

A similar examination of the Luminaire A table show considerably less variation in the rating of similar rooms—20 ft. x 20 ft. and 20 ft. x 100 ft. Shielding of the distant fixtures lessens their contribution to visual discomfort. The visual-comfort indexes vary from 92% to 97% for similar rooms when viewing is either lengthwise or crosswise. In other words, with lighting systems using Luminaire A, the problems of satisfying more sensitive persons would be easily met. There is a significant difference, however, in the rating of long, low-ceilinged rooms whether the luminaires are viewed lengthwise or crosswise.

If such information is given to an office manager he will be better able to decide on an acceptable lighting system. The factors mentioned also form a guide to decoration of walls, ceilings, floors, and desks. Study of the tables give clues to the best way to arrange equipment and seating in a manner to provide visual comfort to the employees.

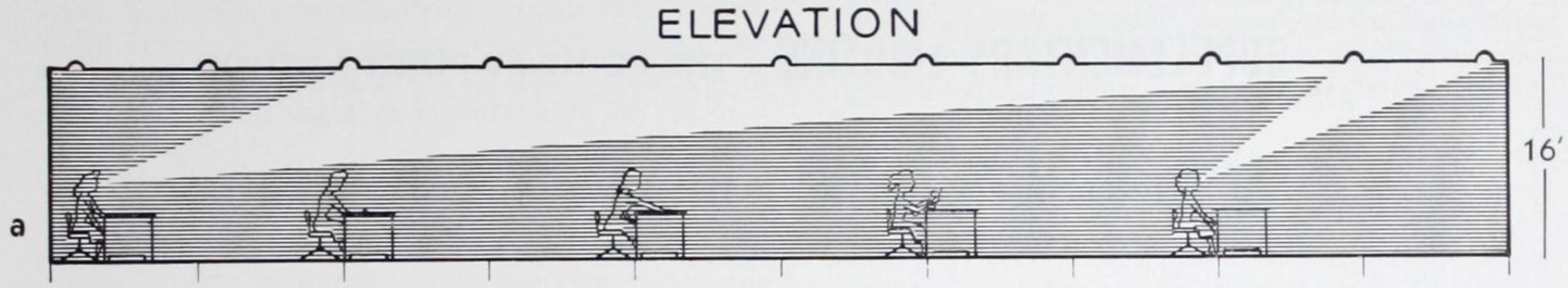


Fig. 97. a. This 20 ft. x 100 ft. office is lighted with Luminaire B; the persons in the back part of the room have more luminaires in view than those in the front part.

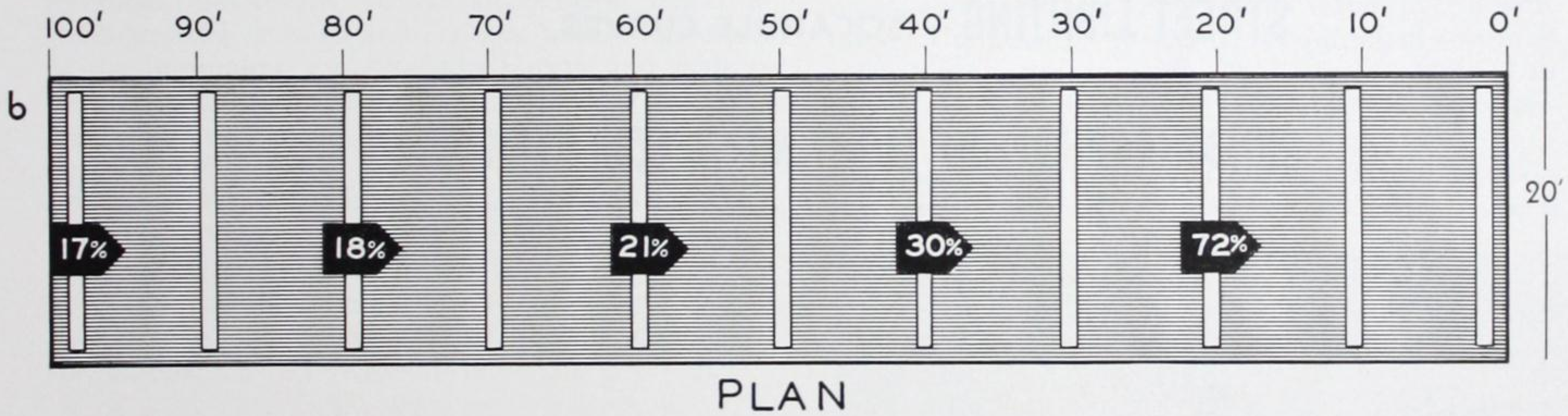


Fig. 97. b. In this plan of the room, visual-comfort indexes are plotted at the points of corresponding room size, for example, the 20 ft x 100 ft. room has an index of 17%, the 20 ft. x 20 ft. room has an index of 72%.

PART VIII

THE DESIGN OF LIGHTING SYSTEMS

GENERAL LIGHTING — THE LUMEN METHOD

SUPPLEMENTARY LIGHTING — THE POINT-BY-POINT METHOD

SUPPLEMENTARY LIGHTING — THE LUMENS-PER-FOOT METHOD

FLOODLIGHTING — THE BEAM-LUMENS METHOD

STREET LIGHTING — ISOCANDLE CURVES

NOMOGRAPHS FOR LIGHTING CALCULATIONS

GENERAL LIGHTING

THE LUMEN METHOD

It is evident from the foregoing study of the variety of materials used in fashioning lighting equipment and the range of control methods that a number of problems arise when lighting equipment is used in interiors. The eye is a poor judge of both illumination and brightness; using a method of design enables the designer to predict results which solve many of these problems.

Lighting systems may be divided into two classes—*general* and *supplementary*. The general system supplies uniform illumination in the area; supplementary lighting supplies illumination of a specific nature, color, or distribution, usually to satisfy a local, specific requirement. Supplementary systems augment the general lighting system, often supplying hundreds of footcandles for certain tasks, machines, or displays.

Other terms for combinations of these are often used. *Localized general* lighting, for example, is a system designed so that rows of work benches, machines or sales counters receive emphasis by spacing the general luminaires with respect to them.

The design of *general* lighting systems is governed by room dimensions, structural features, reflection characteristics of walls and ceilings, mounting height of the luminaires, and the distribution and maintenance characteristics of the luminaire. The choice of the luminaire depends on the service to which it is to be put. This assumes a certain experience in selection, or other aids such as manufacturers' data. These assist the designer in making a selection appropriate from the standpoints of freedom from glare, efficiency, decorative value, and economy. The ultimate "brightness pattern" of the room is an important factor in the design.

The beginning concept of general lighting design is that of delivering a specified average footcandle level of illumination to a horizontal plane in a room. The light generated by the lamps in such a system is variously affected and considerably reduced by reflection, diffusion, and absorption as it impinges on reflectors and transmitting media in the luminaires and on ceilings, walls, floors, and on the objects in the room. The Room Index method of general lighting design takes into account many of these variables in determining the ultimate average lighting level.

THE LUMEN METHOD OF LIGHTING DESIGN

About fifty years ago it became evident that a method of design faster than the prevalent point-by-point calculations, and including the effects of interreflection, was needed for more rapid development of good lighting.

The idea of the lumen method was proposed and studied, but no data came into general use until Harrison and Anderson presented tables of measured utilization data in 1920* with their Three Curve Method of calculation, and their Room Ratio System. These provided a ready procedure for calculating tables of utilization coefficients from photometric data —and these coefficients were easy to use in lighting design.

Recently, however, developments in lamps, luminaires, and lighting practices have indicated a need for further studies. Consequently, extensive measurements have been made by Potter and Russell in experimental rooms such as shown in Fig. 98. The rooms were very flexible—they could be as large as 30 feet square, the ceiling heights could be varied up to 16 feet; various layouts of actual luminaires were readily made, and room surfaces could be varied over a wide range of reflectance. Mechanized equipment was used for recording measurements. The results obtained in these rooms have been correlated with zonal and interflection data derived mathematically.

The basic equation of the Lumen Method gives the total generated lumens required to produce a

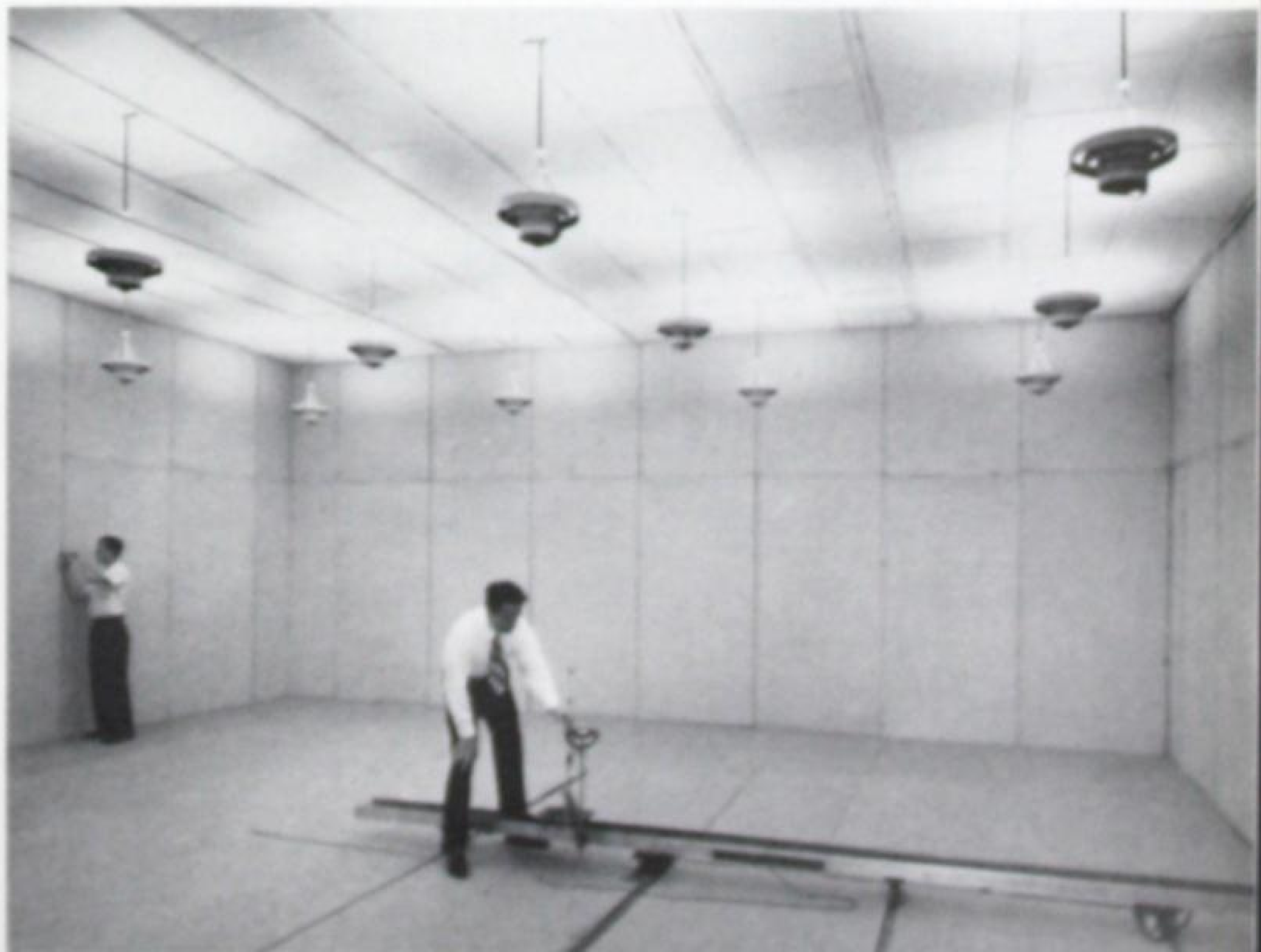


Fig. 98. This test room for determining coefficients of utilization and other data has a movable ceiling, movable walls, and mechanized facilities for making measurements.

* See Measured Utilization Factors II, IE, April, 1955.

selected average illumination on the work-plane or other plane of reference:

$$\text{Required Total Lamp Lumens} = \frac{\text{Fc} \times \text{Area}}{\text{CU} \times \text{MF}}$$

in which:

Fc—the average illumination on the work-plane in footcandles or lumens per square foot.

Area—the area of the room—(work-plane)—in square feet

CU—the Coefficient of Utilization

MF—the Maintenance Factor

Obviously, the numerator is the total lumens which reach the work-plane directly from the luminaires and from room surfaces by interreflection. It takes into account the *desired illumination* and the actual *size* of the room.

In the denominator appear two factors which allow for several important variables which affect the performance of the lighting system. For clarity they may be grouped under two headings as follows:

A. LUMINAIRE CHARACTERISTICS:

Distribution: (*Shape* of candlepower curve)
Efficiency (Fraction of lamp lumens emitted)
Number and Location (with room proportions as a factor)
Maintenance (Effect of dirt or corrosion on distribution and efficiency)

B. ROOM CHARACTERISTICS:

Proportions
Reflectance of interior surfaces and furnishings
Maintenance (Effect of dirt collection on reflectance)

A. LUMINAIRE CHARACTERISTICS

A frequently-used classification of luminaires by **Distribution** follows a rough division of output into downward (0° - 90° lumens) and upward (90° - 180°) lumens as follows:

	% Downward	% Upward
Indirect	0 - 10	90 - 100
Semi-Indirect	10 - 40	60 - 90
General Diffusing	40 - 60	40 - 60
Semi-Direct	60 - 90	10 - 40
Direct	90 - 100	0 - 10

This table is not of assistance in the lumen method, however, because it contains no detailed information on distribution and none on efficiency of the luminaire. Downward light reaches the work-plane with fewer losses than upward light; the latter must all be reflected by room surfaces before any of it is effective on the work-plane. But the amount of downward light reaching the work-plane may be affected by its type of distribution. Obviously a wide 0° - 90° distribution will cause more light to strike the walls than will a narrower or more concentrated downward distribution, and will occasion greater losses by reflection. Moreover, the performance of the various distributions may differ with the patterns of luminaires in rooms of different proportions. But analysis of the candlepower distribution curve is readily performed by detailed zonal calculations or by a simpler procedure using Flux Ratio (an index of concentration) as described below.

The second variable is **Efficiency,** for two luminaires may have similar distributions, but differ in the fraction of lamp lumens emitted, or vice versa. Where necessary it is convenient for calculation to divide this into Upward and Downward Efficiencies.

Next, the **Number and Location** vary from individual spaced luminaires through continuous line patterns and closely-spaced high-mounted units to the extreme of a wall-to-wall louver or panel ceiling. These layout patterns are readily described by the ratio of spacing-to-mounting height—from 1.5 or 1.0 through 0.4 for many direct units and to 0.0 for luminous ceilings. This Spacing-Mounting Height variable causes differing losses due to light absorbed by walls for the same luminaire in different conditions.

The relationship of spacing to height in conjunction with the candlepower distribution of the luminaire also affects the uniformity of illumination on the work-plane. In many interiors essentially uniform illumination over the entire work-plane is needed; in others planned variation may be desirable. The higher the degree of uniformity, the more significant is the average footcandle value as predicted by the Lumen Method. Fig. 99 illustrates the effect of too-large luminaire spacing and the improved effect of correct spacing. Table 7 presents an empirical guide to maximum spacing for certain types of luminaires and suggested distances for the suspension of indirect and semi-indirect luminaires. In the latter cases the controlling factors are the brightness distribution of the ceiling and general appearance of the installation. It should be noted also that even with uniformly bright surface sources such as reflecting or translucent diffusing ceilings, the work-plane illumination is substantially reduced near the walls.

Although the spacing of luminaires is based on their mounting height above the work-plane, their height above the floor is used for convenience in Table 7. With many fairly wide distributions, reasonably uniform illumination results when the ratio of

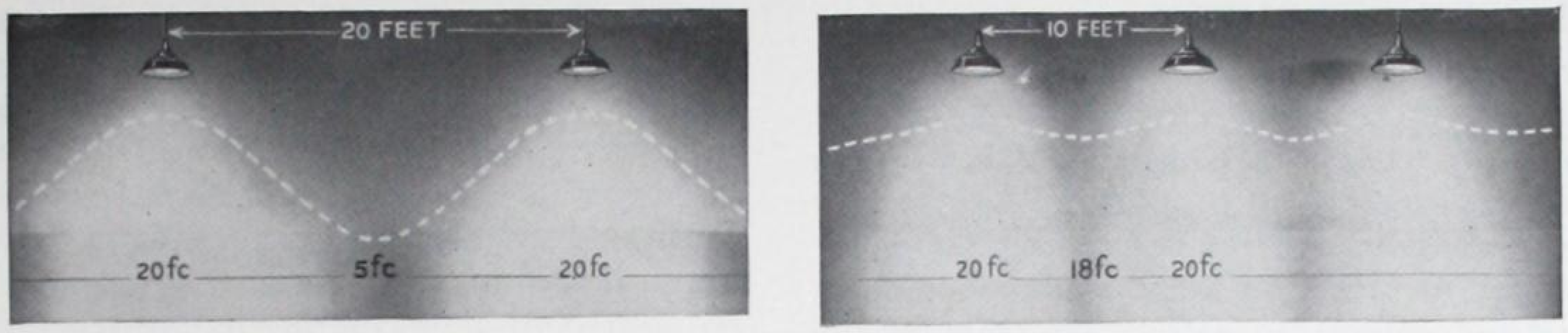


Fig. 99. Too wide spacing produces non-uniform illumination with low spots between luminaires. Correct spacing eliminates such relatively dark areas, makes the whole area visually suitable as work or display space.

TABLE 7 SPACING-MOUNTING HEIGHT OF LUMINAIRES
(All dimensions in feet)

Mounting Height of Luminaires (above floor) except for Indirect and Semi-Indirect Luminaires, use Ceiling Height (above floor)	Suspension Distance For Indirect and Semi-Indirect Luminaires	MAXIMUM* SPACING DISTANCE BETWEEN LUMINAIRES							Distance from Walls All Types of Luminaires
		Indirect	Semi-Indirect	General Diffusing	Semi-Direct	Direct	Semi-Concentrating Direct	Concentrating Direct	
8	1-3	9.5	9.5	8	7	7	6.5	5	
9	1.5-3	10.5	10.5	9	8	8	7	5.5	⅓ Spacing
10	2-3	12	12	10	9	9	8	6	
11	2-3	13	13	11	10	10	9	6.5	Distance if
12	2.5-4	14.5	14.5	12	11	11	9.5	7	desks or
13	3-4	15.5	15.5	13	12	12	10.5	8	work benches
14	3-4	17	17	14	12.5	12.5	11	8.5	are against
15	3-4	18	18	15	13.5	13.5	12	9	walls, other-
16	4-5	19	19	16	14.5	14.5	13	9.5	
18	4-5	22	22	18	16	16	14.5	11	wise ½.
20 or more	4-6	24	24	20	18	18	16	12	

*The actual spacing is usually less than these maximum distances to suit bay or room dimensions or to provide adequate illumination. At an established mounting height, it is often necessary to reduce the spacing between luminaires or rows of them to provide specified footcandles. In such systems and particularly in small rooms, the utilization is reduced because the luminaires are closer to the walls. For example, in an 80-30-10 room with a room ratio of 0.6 and a flux ratio of 0.7, the utilization factor is .79 where the spacing-mounting height ratio is 1.0 (luminaires as far apart as they are above the work-plane). With the same room conditions but with luminaires spaced .4 as far apart as they are above the work-plane, the utilization factor is only .65.

spacing to mounting height above floor does not exceed 1.0, but more concentrated distributions require a lower ratio.

The spacing-mounting height relation applies not these cases only maximum spacing between rows naires or extended luminous elements as well. In these cases only maximum spacing between rows would be determined from the table.

Maintenance of a luminaire combines the effects of the gradual lowering of lamp output during its life and the losses due to depreciation of the luminaire output under different conditions of atmospheric dirt, etc. The Maintenance Factor compensates for the reduced illumination in service by providing the necessary extra illumination when the installation is new.

B. ROOM CHARACTERISTICS

The **Proportions** of rooms effect the utilization of light—large low-ceiling rooms are favorable; higher, narrower ones are less effective. A ROOM RATIO is used as the measure of room proportion with respect to utilization of light; it also describes rectangular rooms in terms of the equivalent square room on which utilization tables are based. The side of the equivalent square room equals the harmonic mean of width and length of the oblong room. The equation is:

$$\text{ROOM RATIO*} = \frac{W \times L}{H\,(W + L)}$$

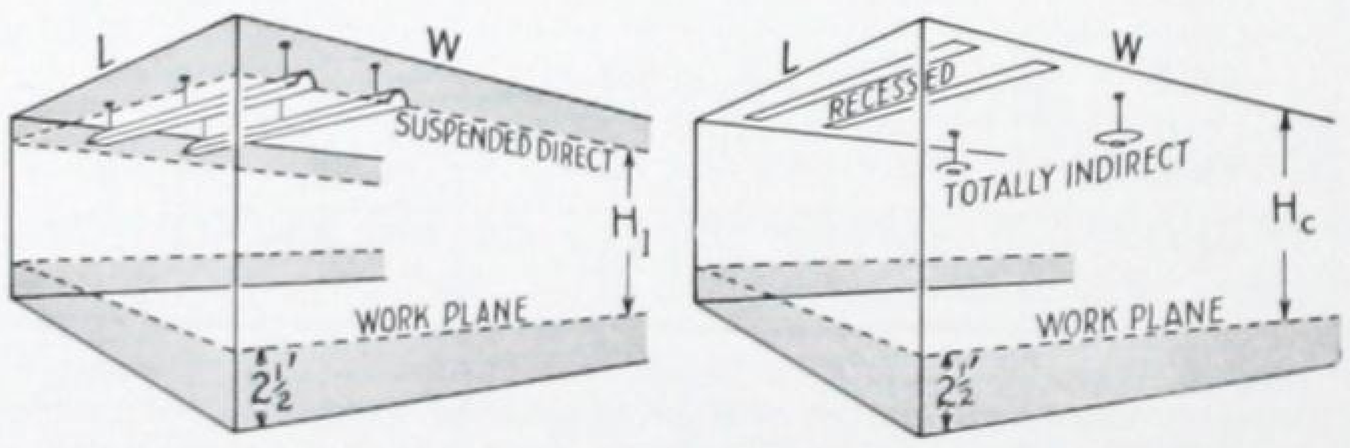
in which:

W = room width;
L = room length;
H = vertical distance from work-plane to the light-center of luminaires or to the ceiling. (All distances are in feet)

This reduces to

$$\text{ROOM RATIO} = \frac{W}{2H} \text{ for square rooms,}$$

which is the familiar generally-used "Direct Lighting" form originated by Harrison and Anderson. It will be noted that it is based upon the relationship of the principal sources of light (luminaires or ceiling) to the work-plane, not upon overall room height. The equation above has been used generally only for downward light (Ref. I.E.S. Handbook), but in this publication it is employed for systems with "indirect" as well as "direct" components.



As seen in the sketch, the height "H" depends upon the type of lighting system; with suspended direct luminaires H_1 is used. This is measured from the Light Center of the unit to the work-plane. For flush-mounted systems such as troffers, recessed downlights, and luminous ceilings H_c is used. This is measured from the ceiling to the work-plane. In totally indirect systems, the ceiling is the principal light source so H_c is used here also. Room Ratios for a limited range of room sizes are given in Table 8, page 70.

* This also has been termed Room Index with letters to represent the following numerical room ratios in Table 8: 0.6-J; 0.8-I; 1.0-H; 1.25-G; 1.5-F; 2.0-E; 2.5-D; 3.0-C; 4.0-B; 5.0-A

The **Reflectances** of room boundary surfaces (ceiling, walls, floor, etc.) are important factors in the overall utilization of a lighting system as well as in the quality or comfort aspects of the installation. The higher values are usually preferred where severe and continued visual tasks are prevalent. Often, however, lower reflectances for certain surfaces or rooms may be desired in a specific decorative scheme. Moreover, data for low as well as high reflectances facilitate comparative analyses. Utilization data are given in Table 9 for various combinations of ceiling, wall and floor reflectances and thus allow interpolation. Reflectances represent averages (for example, for walls the reflectances of windows, doors and woodwork are included).

Room surfaces may change in reflectance due to accumulations of dirt or to discoloration over a period of time. This affects the average illumination in service and is allowed for in the **Maintenance Factor** applicable to the installation.

UTILIZATION FACTOR AND COEFFICIENT OF UTILIZATION

The effects of all the above mentioned variables except Efficiency and Maintenance are combined in the UTILIZATION FACTOR. This represents the fraction of the luminaire light output which reaches the work-plane.

$$\text{UTILIZATION FACTOR (UF)} = \frac{\text{Fc} \times \text{Area (of work-plane)}}{\text{Total } \textit{Luminaire} \text{ Output in Lumens}}$$

This basic factor is given by charts such as Figs. 102 and 103.

When utilization data are tabulated for a specific luminaire, however, it is easier to use Coefficient of Utilization which also includes the luminaire efficiency. The COEFFICIENT OF UTILIZATION represents the fraction of lamp output which reaches the work-plane.

$$\text{COEFFICIENT OF UTILIZATION (CU)} = \frac{\text{Fc} \times \text{Area (of work-plane)}}{\text{Total } \textit{Lamp} \text{ Output in Lumens}}$$

Or CU = UF x Efficiency of Luminaire.

The Coefficient of Utilization for a lighting system may be determined by measurement, calculation, or both. At present it is calculated for each of two components of luminaire output (downward and upward); then the two coefficients are added to give the overall Coefficient of Utilization.

Coefficient of Utilization—Downward (Direct) Components

Light directed strongly downward reaches the work-plane directly; light at wider angles strikes the walls and is partly absorbed; the amount of absorption depends upon the size of the room and the reflectance of the walls.

From the candlepower distribution curve of a luminaire, the lumens in each 10° zone from 0° to 90°

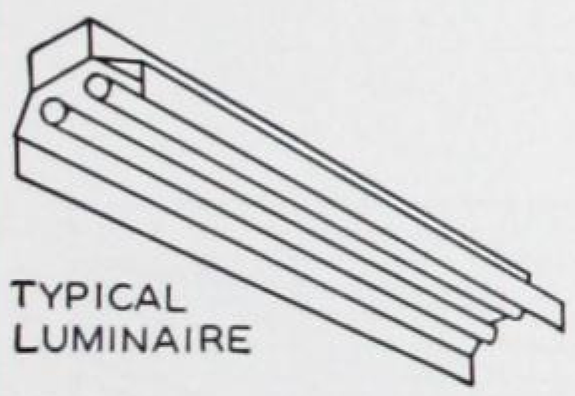
can be calculated. In general, however, it is only those in the 0° - 60° zone which substantially contribute direct lumens toward the work-plane. By applying a weighting factor to each of these six 10° zones one can estimate the relative effectiveness of all the lumens. The multiplying factors* used for each zone are as follows:

Zone	**Multiplying Factor**	
0 - 10 degrees	1.00	These factors have been found effective in appraising a flux distribution with respect to utilization under a variety of conditions.
10 - 20 degrees	.83	
20 - 30 degrees	.65	
30 - 40 degrees	.50	
40 - 50 degrees	.33	
50 - 60 degrees	.16	

A summation of the effective zonal lumens divided by the 0 - 90° lumens is called Flux Ratio** which is expressed as follows:

$$\text{Flux Ratio} = \frac{a + .83b + .65c + .50d + .33e + .16f}{\text{Lumens in } 0^\circ - 90^\circ \text{ zone}}$$

where a is the 0° - 10° zone lumens; b = 10° - 20°; c = 20° - 30°; d = 30° - 40°; e = 40° - 50°; and f = 50° - 60° zone lumens. Flux Ratio values are used as the abscissae in typical pre-calculated charts of Utilization Factors such as Figs. 102 and 103.



TEST SUMMARY		
ZONE	ZONE LUMENS	% TOTAL LAMP
0-10	121	
10-20	351	
20-30	580	
30-40	681	
40-50	737	
50-60	688	
0-90	4000	80
90-180	0	0
0-180	4000	80

TOTAL LAMP LUMENS—5000

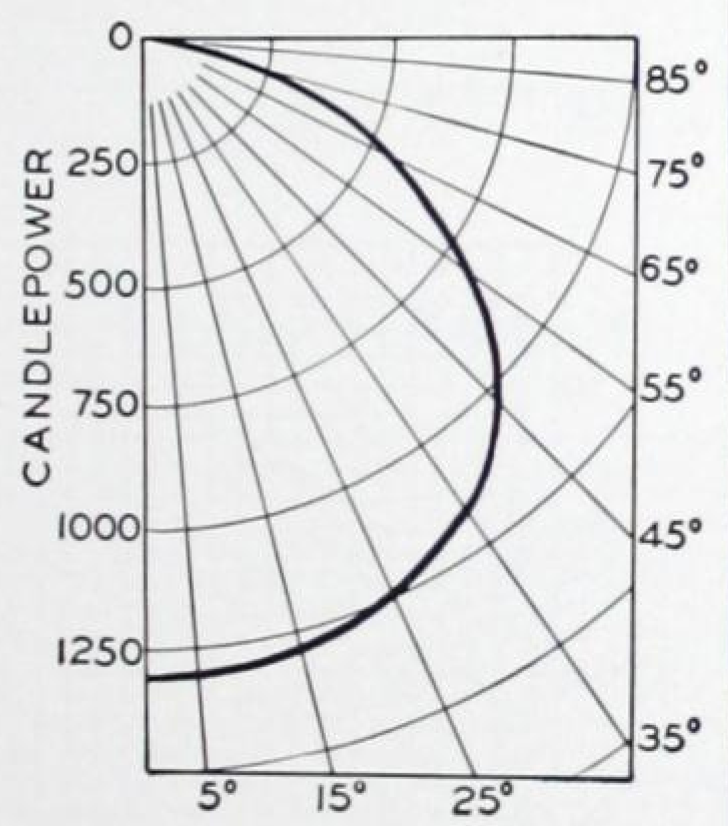


Fig. 100. Candlepower distribution curve for a typical two 40-watt T-12 fluorescent industrial luminaire.

The test data for a typical luminaire which distributes all of its light downward is shown in Fig. 100. Suppose a system of these luminaires is suspended 18 inches below the ceiling and properly spaced to illuminate a room uniformly. Assume the room is 30′ by 35′ with a 12′ ceiling and with 80% ceiling, 50% walls, and a 10% floor. The height H_1 is equal to 8 feet (above a 2½ ft. work-plane). Then

* See Measured Utilization Factors II, "Illuminating Engineering," April, 1955

** Utilization values determined by use of this Flux Ratio, may in extreme cases, depart from the true value by a few per cent.

a. Direct Room Ratio $= \frac{W \times L}{H\,(W + L)} = \frac{30 \times 35}{8 \times 65} = 2.0$

b. To determine the direct coefficient of utilization, first calculate the Flux Ratio (for zone lumens, see data, Fig. 100), which is equal to

$$\frac{121 + (.83\text{x}351) + (.65\text{x}580) + (.50\text{x}681) + (.33\text{x}737) + (.16\text{x}688)}{4000} = .37$$

From Fig. 102a for suspended luminaires, for a flux ratio of 0.37 and a Room Ratio of 2.0, in an 80–50–10 room (80% ceiling, 50% walls, and 10% floor), we find a utilization factor of .817. Figs. 102b and 102c show .75 and .695 utilization factors when the rooms are 80–30–10 and 80–10–10, respectively.

These utilization factors multiplied by the efficiency of the luminaire (.80) give the overall coefficients of utilization. Summarizing—

For the 80–50–10 room, C.U. = .817 × .80 = .65
For the 80–30–10 room, C.U. = .75 × .80 = .60
For the 80–10–10 room, C.U. = .695 × .80 = .56

These three values will be found in the 80% ceiling column in Table 9, page 71, for the direct luminaire having an efficiency of .80 and for a Room Ratio of 2.0.

Upward (Indirect) Components

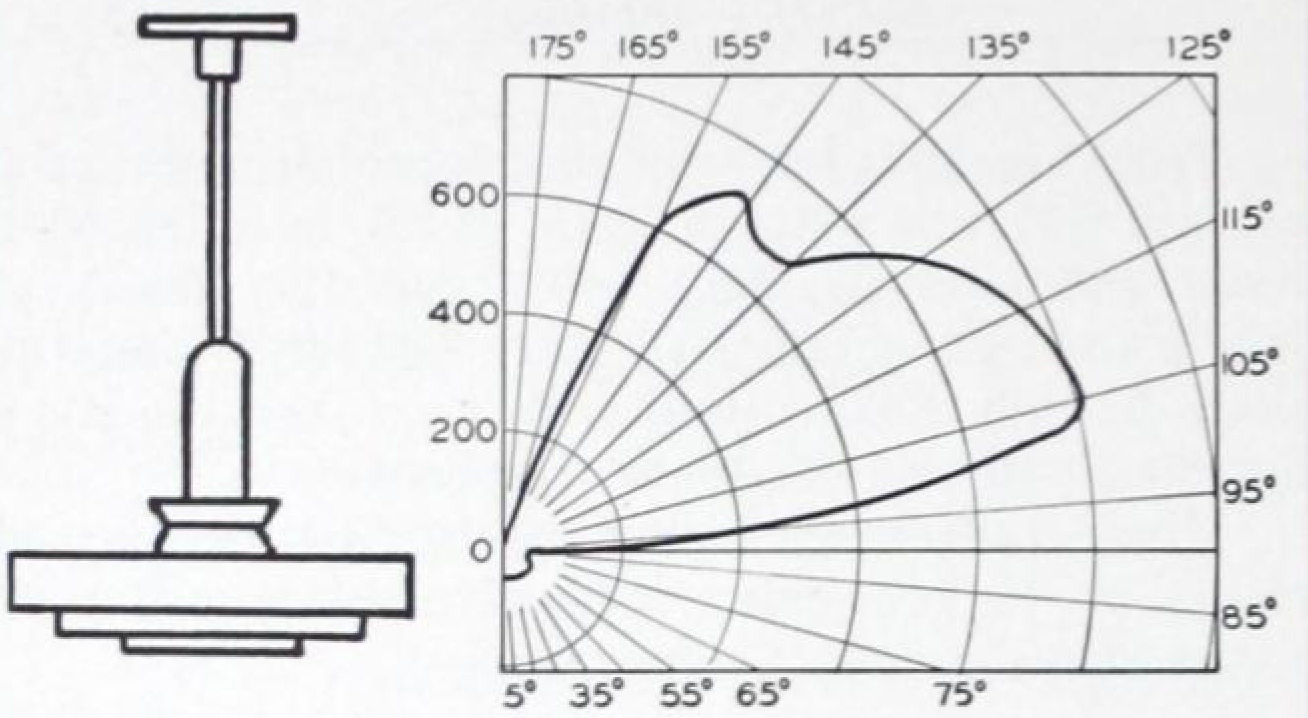
The upward light which reaches the work-plane from luminaires, is reflected from the ceiling and upper walls, and of course, by interreflection from all the room surfaces. Of these, the ceiling is the most important because it receives more of the light directly and because it acts as a luminous source with respect to the work-plane.

Accordingly, rooms with high-reflectance ceilings are more efficient. Utilization is also affected by two other factors. If the ceiling were uniformly bright, one square foot near a wall would reflect as many lumens as any other. Calculated values of utilization are useful for this assumed condition. However, more reflected lumens would be intercepted by the walls and fewer would reach the work-plane than would be obtained from typical wide-distribution indirect luminaires. When such indirect luminaires are used, the higher-brightness ceiling areas somewhat removed from the walls result in higher room utilization.

The other factor—the trapping of ceiling-reflected light by the luminaires themselves—operates to reduce utilization. The reduction is greatest with extensive fluorescent systems which are relatively opaque to ceiling-reflected light. This is especially true with short suspension distances. For evaluating these effects, measurements are preferred and have been made for various rooms, reflectances, and suspension distances. The utilization data of Figs. 105a and 105b are derived from measured data.*

Downward and Upward Components Combined

When the luminaires used in the lighting system have both upward and downward components, it is necessary to calculate two room ratios and two corresponding coefficients of utilization.



TEST SUMMARY		
ZONE	ZONE LUMENS	% TOTAL LAMPS
0-10	5	
10-20	15	
20-30	25	
30-40	33	
40-50	41	
50-60	44	
0-90	265	5
90-180	4505	85
0-180	4770	90

TOTAL LAMP LUMENS—5300

Fig. 101. Candlepower distribution curve for a typical indirect luminaire using a 300-watt silver bowl filament lamp.

For example, assume a luminous indirect filament luminaire (Fig. 101) with 85% of the lumens directed upward and 5% downward. Suppose such luminaires are suspended 24″ from the ceiling and properly spaced to illuminate a room 30′ x 30′ with a 12½ ft. ceiling. Assume room finishes of 80–50–10. Then with H_1 equal to 8 ft. (above a 2½ ft. work-plane).

a. Direct Room Ratio $= \dfrac{W \times L}{H\,(W + L)} = \dfrac{30 \times 30}{8 \times 60} = 1.9$

b. To find the direct coefficient of utilization, calculate the flux ratio from the data in Fig. 101:

$$\text{Flux Ratio} = \frac{5 + (.83x15) + (.65x25) + (.50x33) + (.33x41) + (.16x44)}{265} = .27$$

From Fig. 102a with a flux ratio of .27 and a room ratio of 1.9, the utilization factor is .73 for an 80–50–10 room. From Figs. 102b and 102c, we find .63 and .56 as the utilization factors for 80–30–10 and 80–10–10 rooms, respectively. These factors multiplied by the per cent downward lumens (Downward Efficiency 5%) give the direct coefficients of utilization:

For the 80–50–10 room, the Direct C.U. is $.73 \times .05 = .04$
For the 80–30–10 room, the Direct C.U. is $.63 \times .05 = .03$
For the 80–10–10 room, the Direct C.U. is $.56 \times .05 = .03$

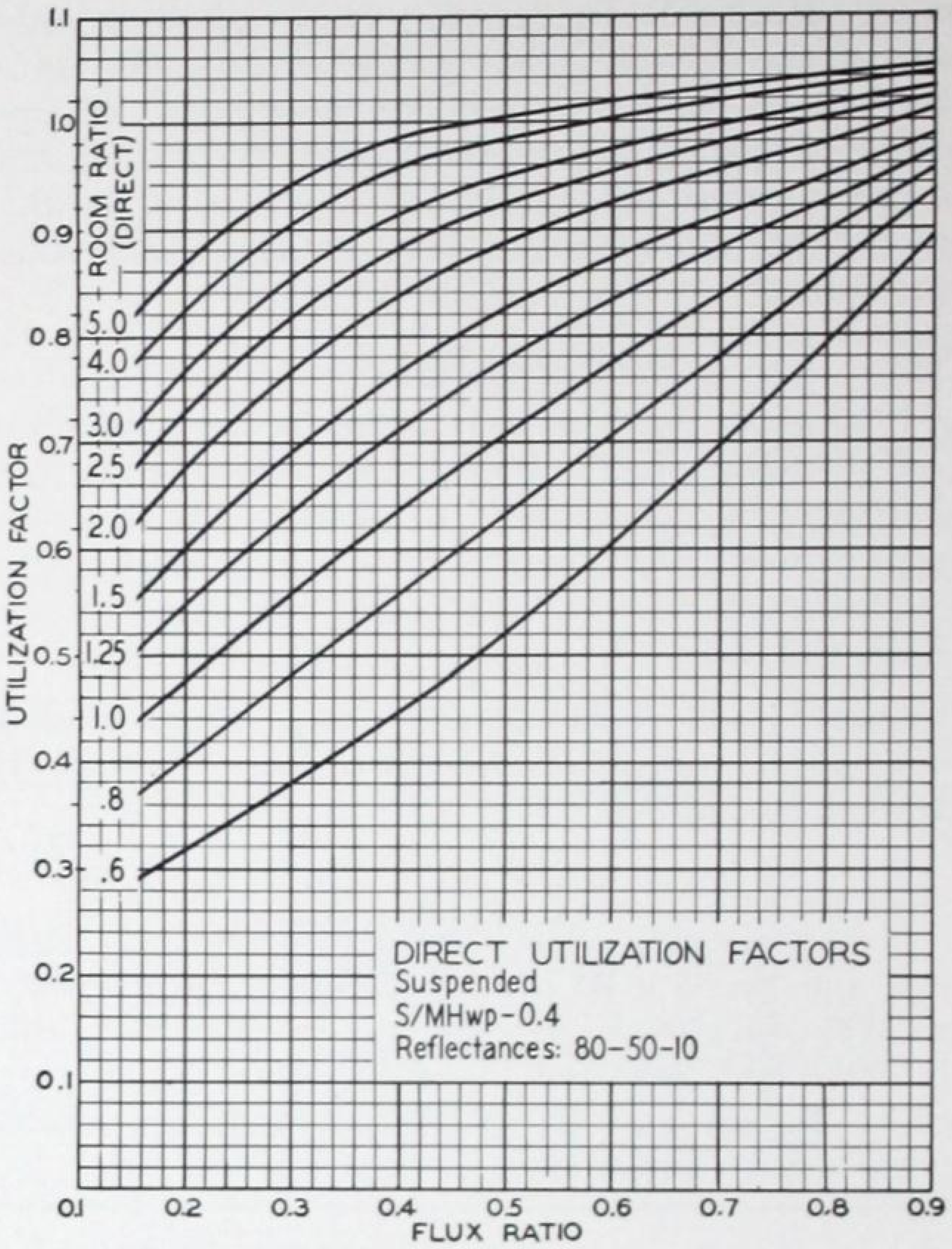


Fig. 102 a

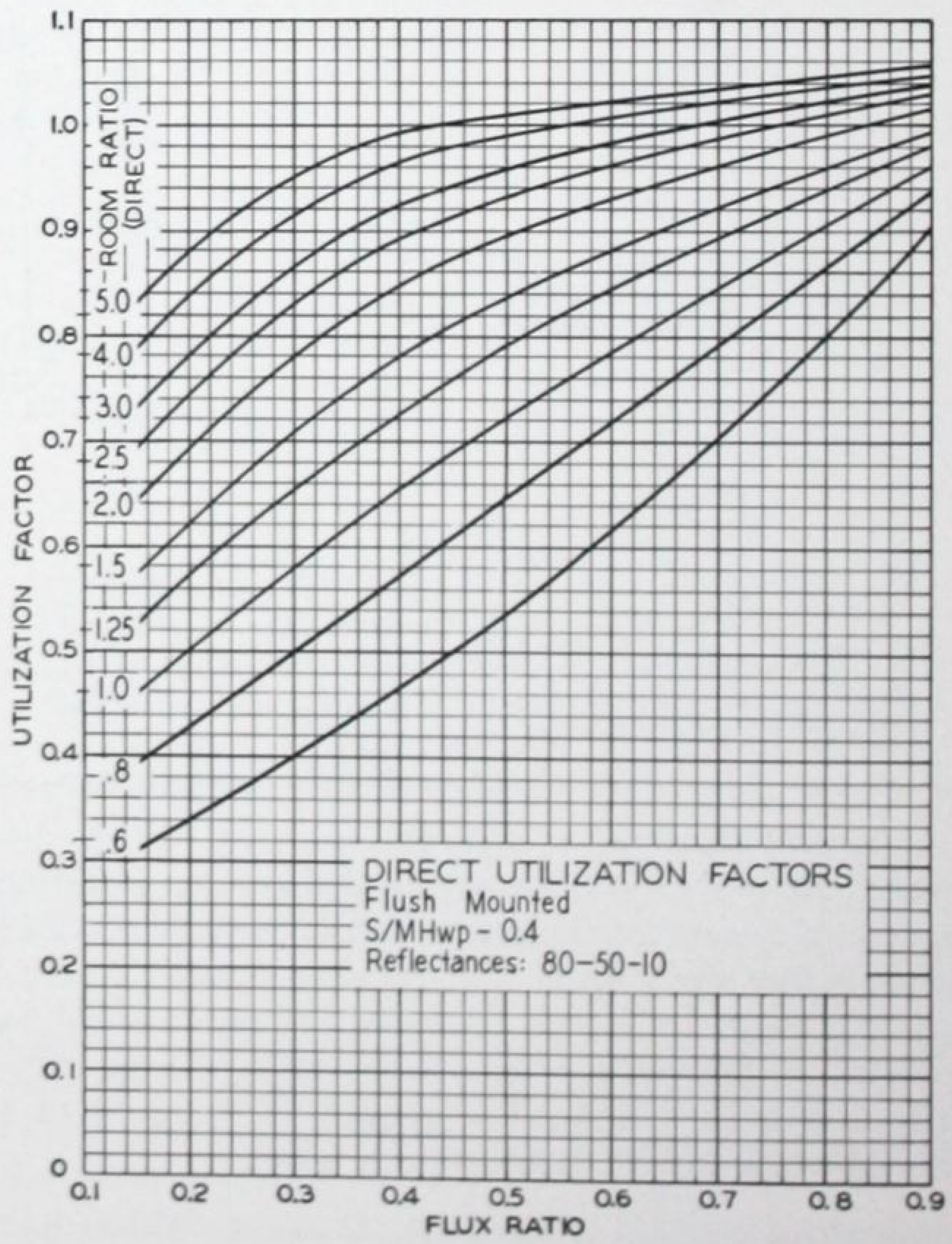
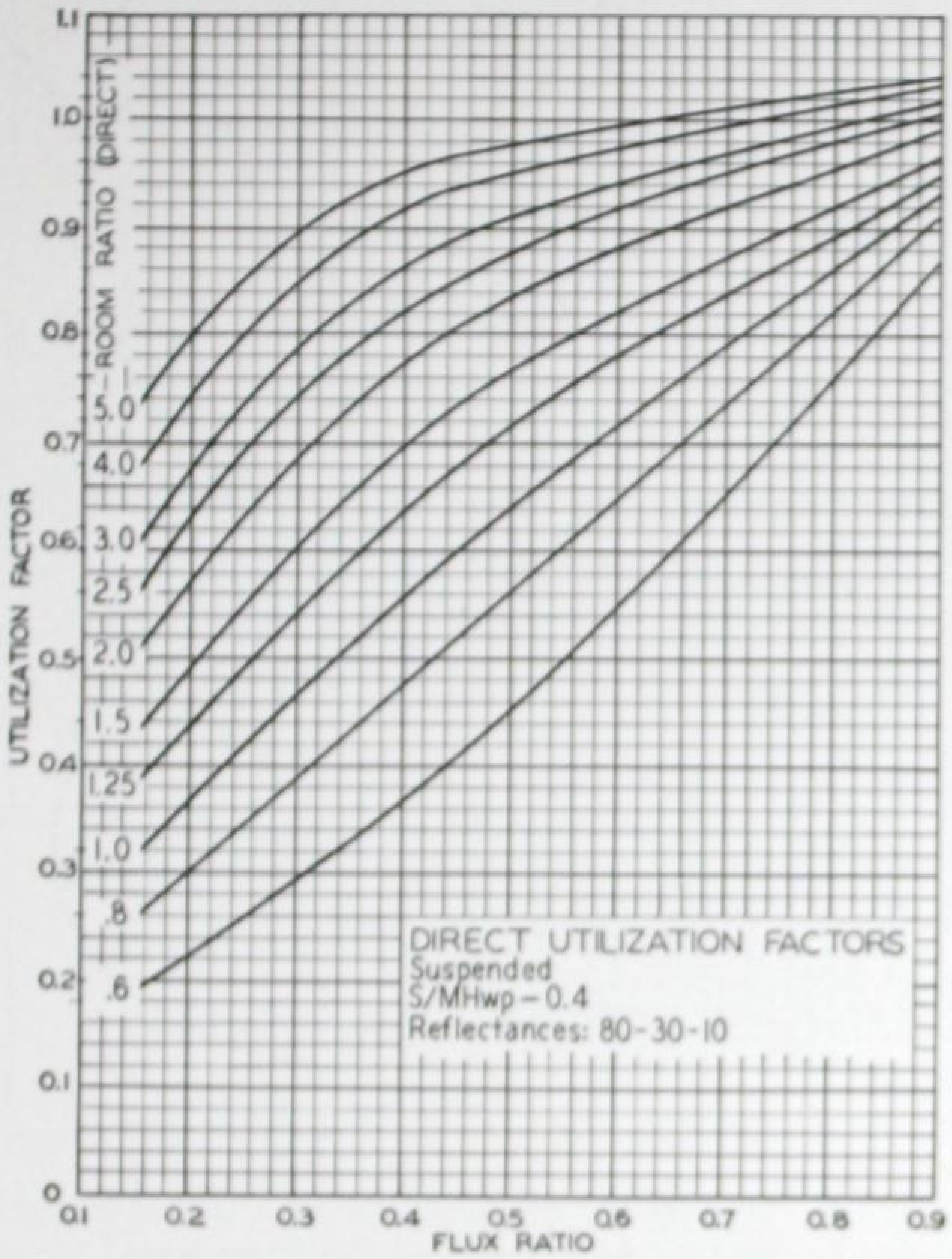
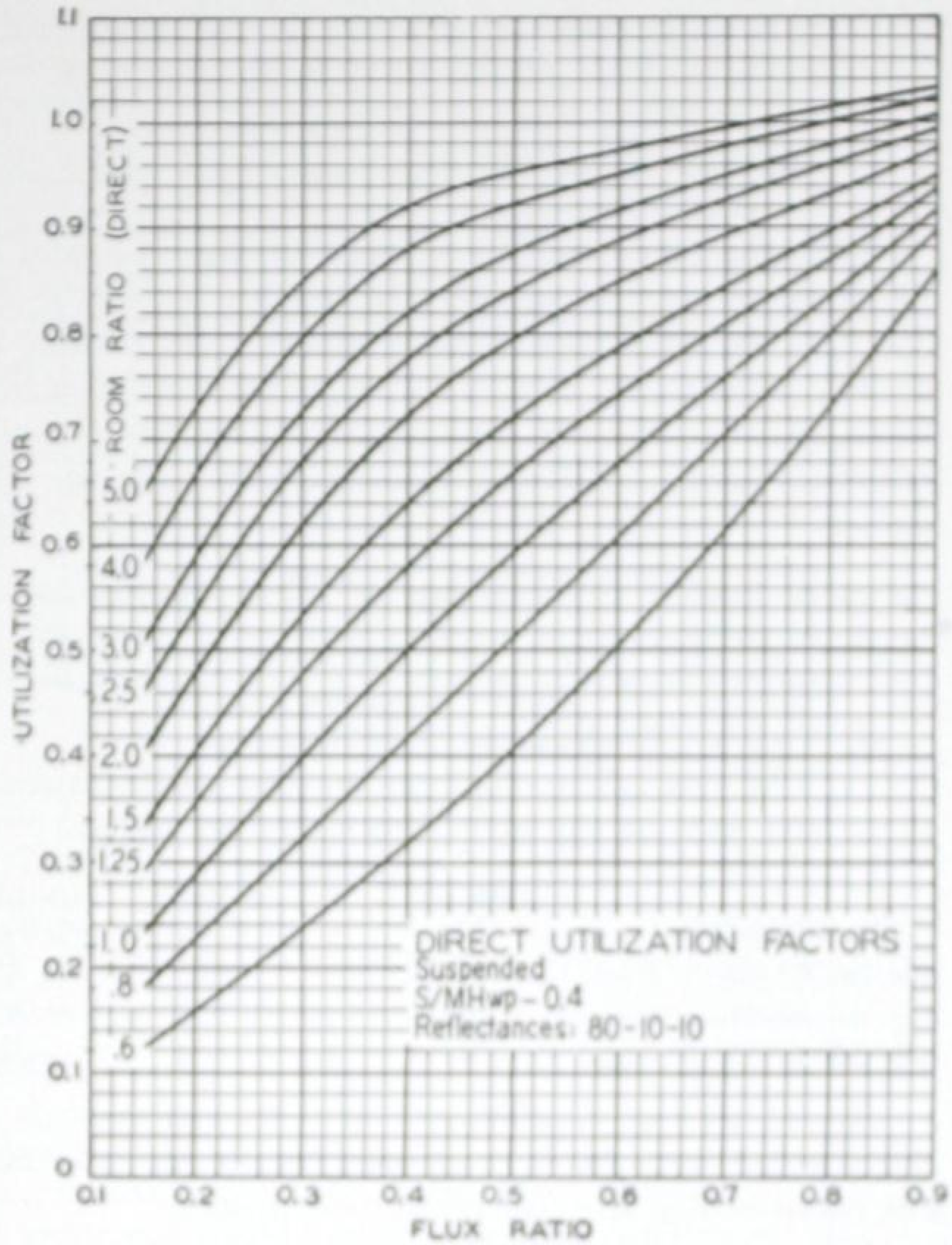


Fig. 103 a

◀ SUSPENDED LUMINAIRES ▶

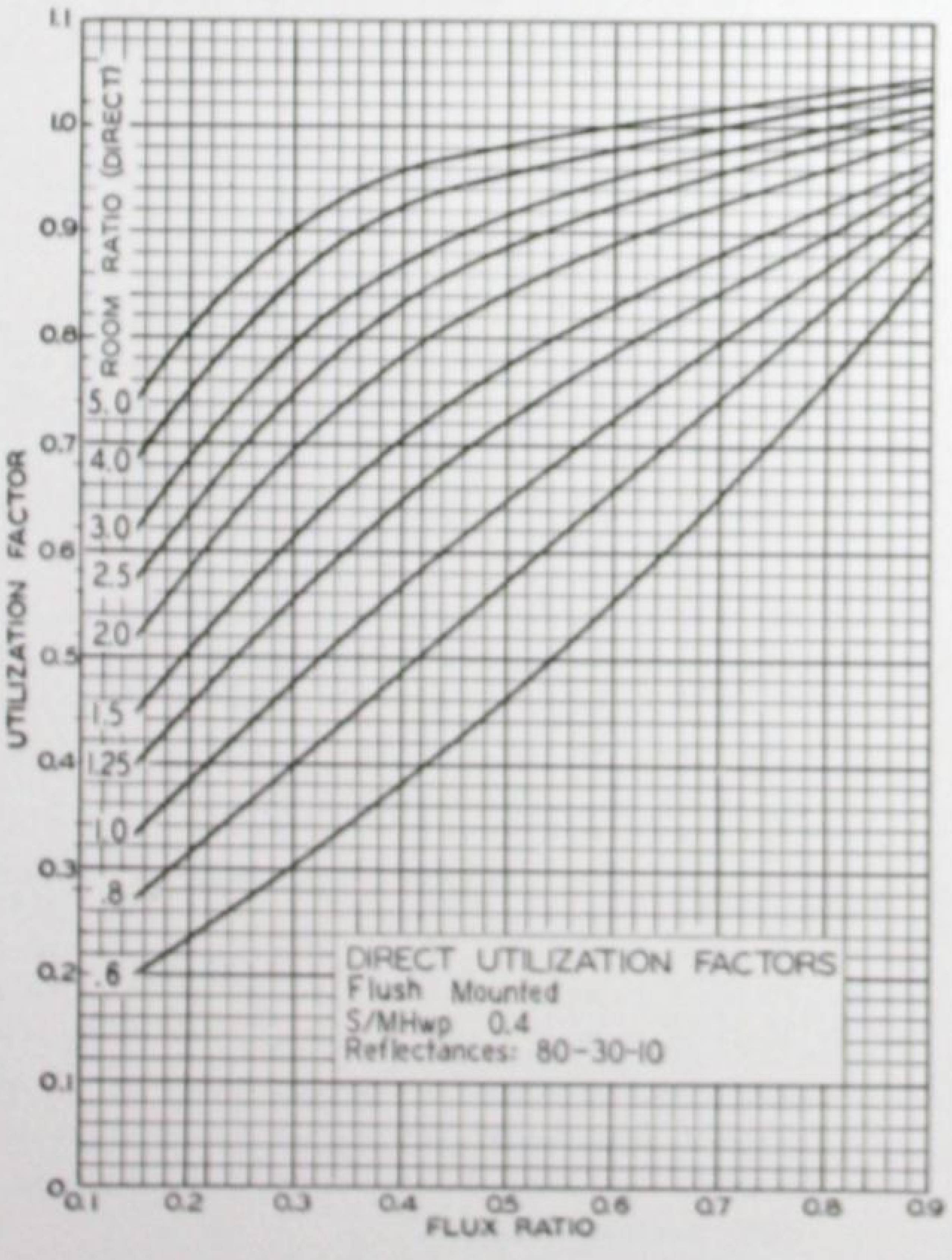


102 b

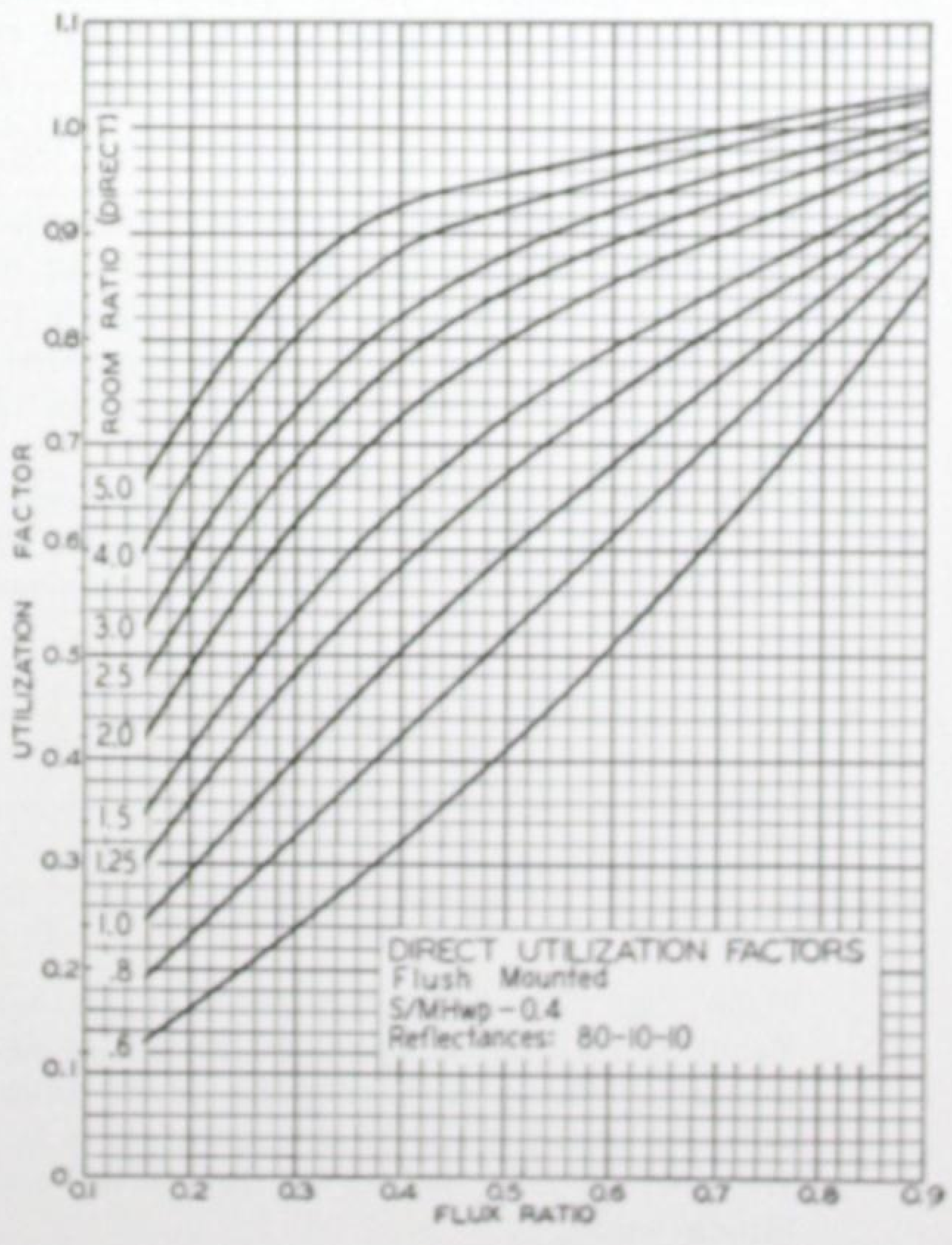


102 c

◀ CEILING (Flush Mounted) LUMINAIRES ▶



103 b



103 c

c. Indirect Coefficient of Utilization

To find the indirect coefficient of utilization, first calculate the indirect room ratio, using $H_c = 10$ feet (above a $2\frac{1}{2}$ ft. work-plane).

$$\text{Indirect Room Ratio} = \frac{30 \times 30}{10 \times 60} = 1.5$$

Then in Fig. 105b for a room ratio of 1.5 and an 80–50–10 room, the indirect utilization factor is .53. For an 80–30–10 room, the indirect U.F. is .47; for an 80–10–10 room, it is .41. These utilization factors multiplied by the per cent upward lumens (Upward Efficiency 85%) give the indirect coefficients of utilization.

For the 80–50–10 room, the indirect C.U. is $.53 \times .85 = .45$
For the 80–30–10 room, the indirect C.U. is $.47 \times .85 = .40$
For the 80–10–10 room, the indirect C.U. is $.41 \times .85 = .35$

d. Overall Coefficients of Utilization

The overall coefficients of the utilization are the sum of the direct and indirect values.

Summarizing,	Direct C.U.		Indirect C.U.	Overall C.U.
For the 80–50–10 room,	.04	+	.45	= .49
For the 80–30–10 room,	.03	+	.40	= .43
For the 80–10–10 room,	.03	+	.35	= .38

In tabulating Coefficients of Utilization such as these which have been computed by use of two different room ratios, the following rule applies:

When the downward light from the luminaire is 40% or more of its output, the direct component has the greater effect and therefore the direct room ratio only is used in tabulating the overall coefficients of utilization. When the downward light is less than 40% of the luminaire output, the indirect component is more important and the indirect room ratio is applicable.

e. Since the luminaire in the example directs more than 60% of its light upward, the indirect room ratio of 1.5 is used in Table 9, page 71. The above three values will be found in the 80% ceiling column for the luminous indirect luminaire.

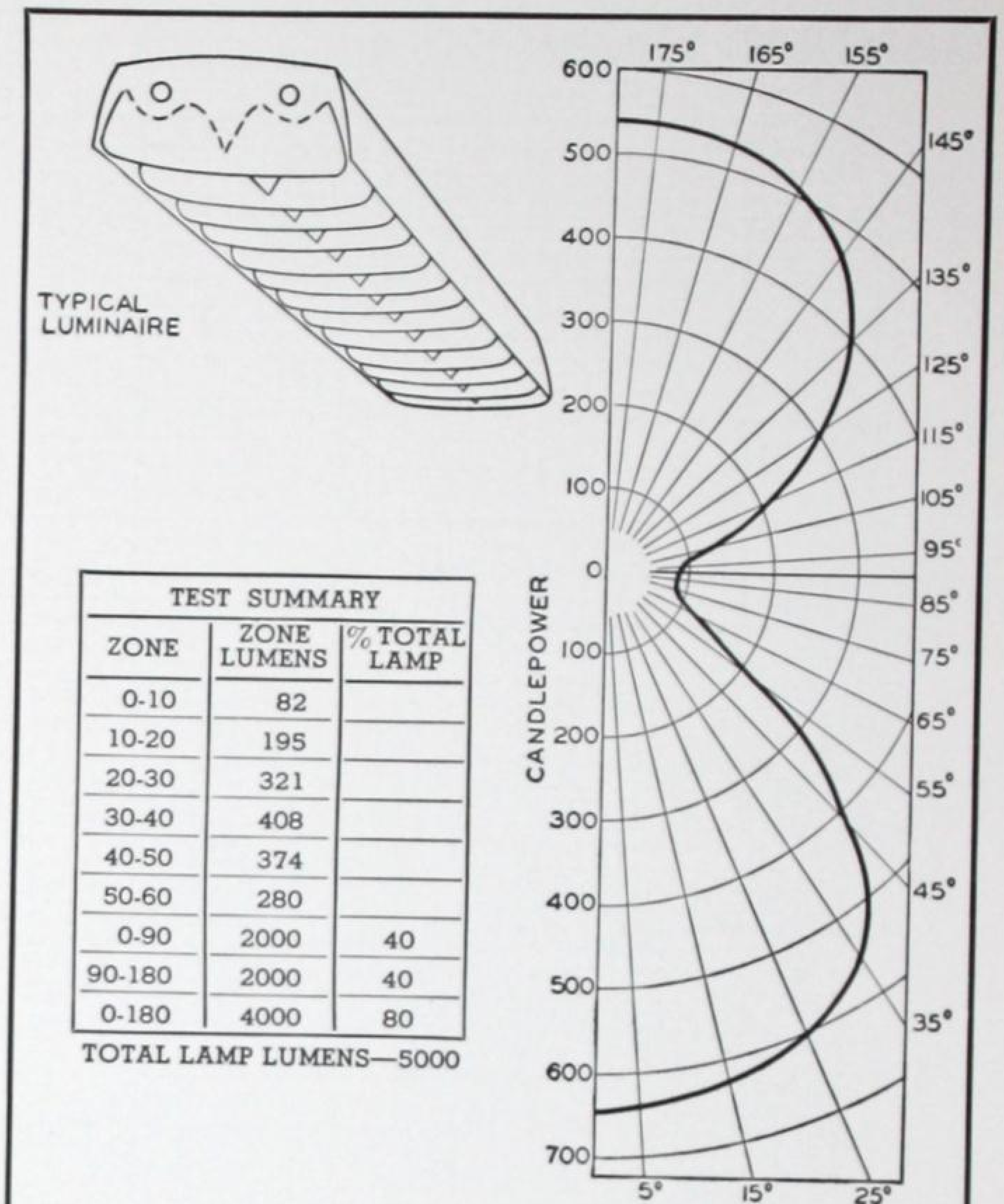
A similar computation may be made for a general diffusing luminaire (Fig. 104). Assume a room 30′ x 35′ with a 11′ 9″ ceiling with luminaires suspended 15″, then with $H_1 = 8'$,

a. $\text{Direct Room Ratio} = \dfrac{W \times L}{H\,(W + L)} = \dfrac{30 \times 35}{8 \times 65} = 2.0$

b. From the data of Fig. 104, the

$$\text{Flux Ratio} = \frac{82 + (.83\text{x}195) + (.65\text{x}321) + (.50\text{x}408) + (.33\text{x}374) + (.16\text{x}280)}{2000} = .41$$

From Fig. 102a for a flux ratio of .41 Room Ratio of 2.0 and an 80–50–10 room, we find a utilization factor of .84. For the 80–30–10 room, it is .78, and for the 80–10–10 room, it is .73. Multiplying these values by the .40 downward lumen value,



TEST SUMMARY		
ZONE	ZONE LUMENS	% TOTAL LAMP
0-10	82	
10-20	195	
20-30	321	
30-40	408	
40-50	374	
50-60	280	
0-90	2000	40
90-180	2000	40
0-180	4000	80

TOTAL LAMP LUMENS—5000

Fig. 104. Candlepower distribution curve for typical general diffusing luminaire for two 40-watt T-12 fluorescent lamps.

For the 80–50–10 room, the direct C.U. is $.84 \times .40 = .34$
For the 80–30–10 room, the direct C.U. is $.78 \times .40 = .31$
For the 80–10–10 room, the direct C.U. is $.73 \times .40 = .29$

c. The Indirect Room Ratio, with an H_c value of 9.25 is:

$$\text{Indirect Room Ratio} = \frac{30 \times 35}{9.25 \times 65} = 1.7$$

d. Indirect Coefficients of Utilization

From Fig. 105a with a Room Ratio of 1.7, an 80–50–10 room shows a utilization factor of .48. For an 80–30–10 room, it is .43. For an 80–10–10 room, it is .38. These factors multiplied by the per cent upward lumens (40%) gives the indirect coefficients of utilization:

For the 80–50–10 room, the indirect C.U. is $.48 \times .40 = .19$
For the 80–30–10 room, the indirect C.U. is $.43 \times .40 = .17$
For the 80–10–10 room, the indirect C.U. is $.38 \times .40 = .15$

e. The overall coefficients of utilization are the sums of the direct and indirect:

Summarizing,	Direct C.U.		Indirect C.U.	Overall C.U.
For the 80–50–10 room,	.34	+	.19	= .53
For the 80–30–10 room,	.31	+	.17	= .48
For the 80–10–10 room,	.29	+	.15	= .44

Since this luminaire directs 50% of its light output downward, the direct room ratio of 2.0 is used in Table 9. The three values are in the 80% ceiling column.

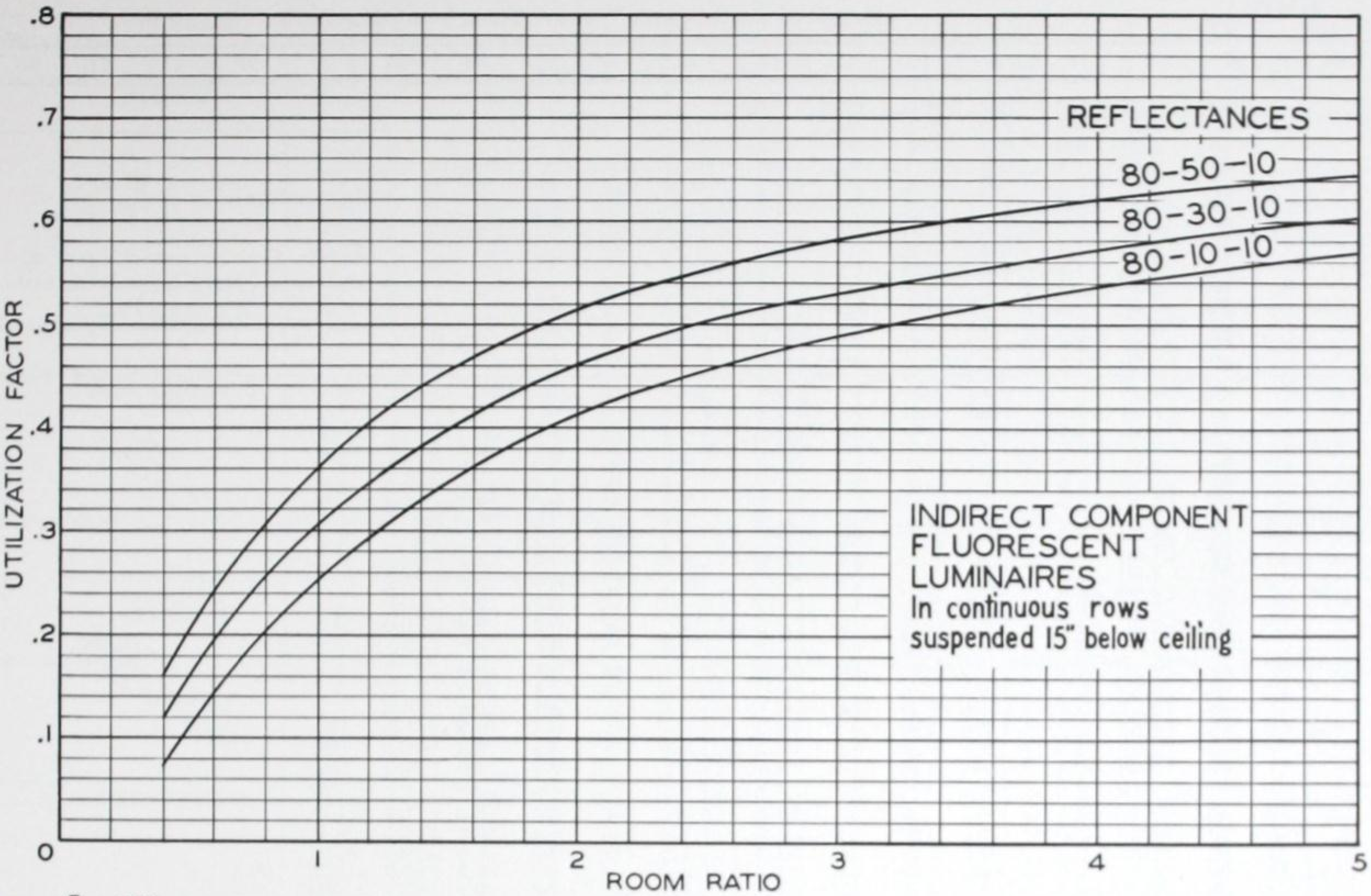


Fig. 105 a

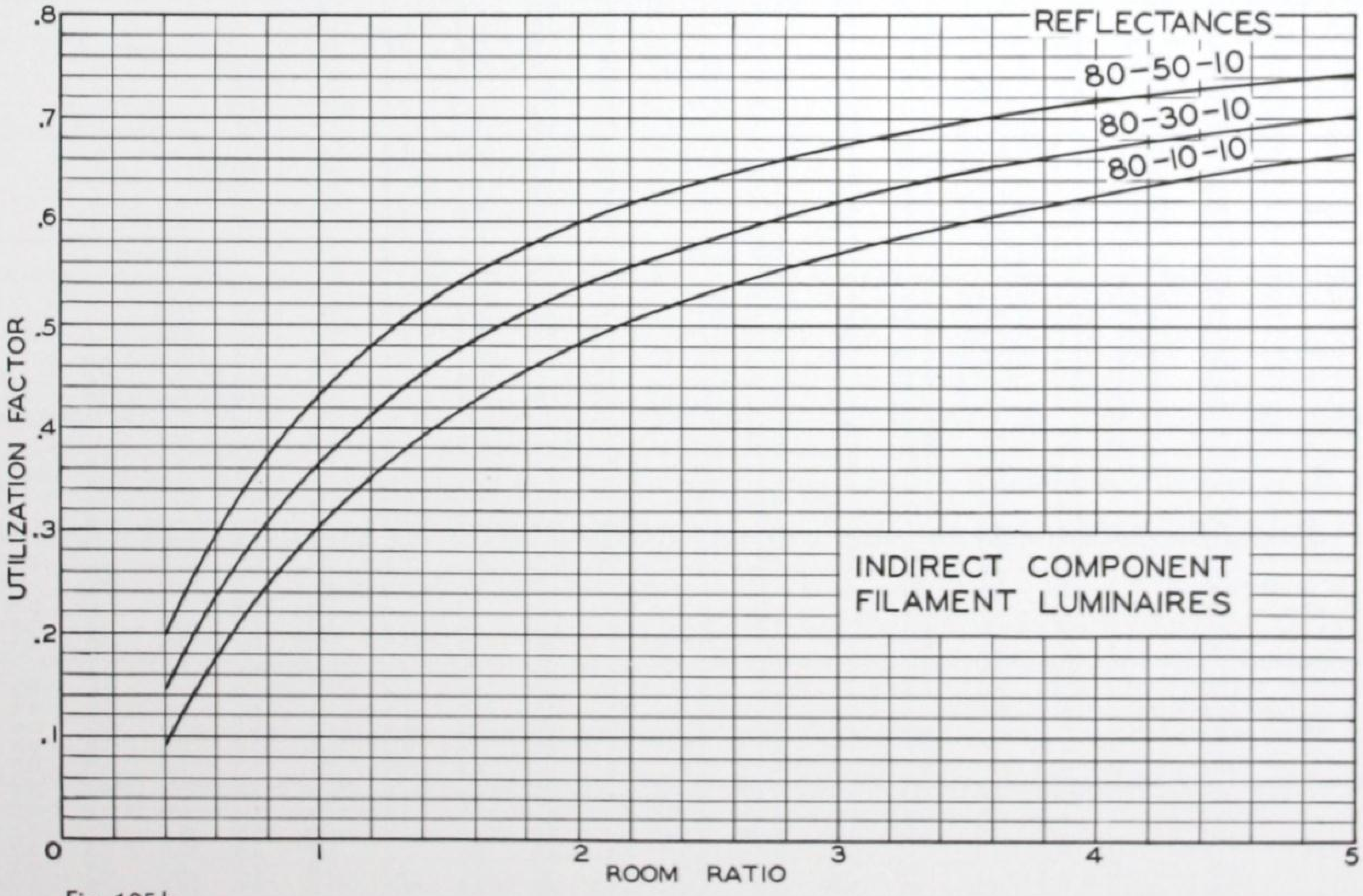


Fig. 105 b

The Utilization Factor for the indirect component of a lighting system can be obtained from sets of curves such as these. The three numbers on each curve represent the reflectances of ceiling, walls, floor.

TABLE 8—ROOM RATIOS *

ROOM W ft.	L ft.	Height of Light Source** above Floor (feet) (H+2½')															
		7	8	9	10	11	12	13	15	17	19	23	27	33	43	53	63
8	10	1.0	0.8	0.7	0.6	0.5											
	14	1.1	0.9	0.8	0.7	0.6	0.5										
	18	1.2	1.0	0.9	0.7	0.7	0.6	0.5									
	24	1.3	1.1	0.9	0.8	0.7	0.6	0.6	0.5								
	30	1.4	1.2	1.0	0.8	0.7	0.7	0.6	0.5								
	40	1.5	1.2	1.0	0.9	0.8	0.7	0.6	0.5								
	50	1.5	1.3	1.1	0.9	0.8	0.7	0.7	0.6	0.5							
10	10	1.1	0.9	0.8	0.7	0.6	0.5										
	14	1.3	1.1	0.9	0.8	0.7	0.6	0.6	0.5								
	18	1.4	1.2	1.0	0.9	0.8	0.7	0.6	0.5								
	24	1.6	1.3	1.1	0.9	0.8	0.7	0.7	0.6	0.5							
	30	1.7	1.4	1.2	1.0	0.9	0.8	0.7	0.6	0.5							
	40	1.8	1.5	1.2	1.1	0.9	0.8	0.8	0.6	0.6	0.5						
	60	1.9	1.6	1.3	1.1	1.0	0.9	0.8	0.7	0.6	0.5						
12	12	1.3	1.1	0.9	0.8	0.7	0.6	0.6	0.5								
	16	1.5	1.2	1.1	0.9	0.8	0.7	0.7	0.5								
	20	1.7	1.4	1.2	1.0	0.9	0.8	0.7	0.6	0.5							
	30	1.9	1.6	1.3	1.1	1.0	0.9	0.8	0.7	0.6	0.5						
	50	2.1	1.8	1.5	1.3	1.1	1.0	0.9	0.8	0.7	0.6	0.5					
	70	2.3	1.9	1.6	1.4	1.2	1.1	1.0	0.8	0.7	0.6	0.5					
	100	2.4	1.9	1.6	1.4	1.3	1.1	1.0	0.9	0.7	0.7	0.5					
14	14	1.6	1.3	1.1	0.9	0.8	0.7	0.7	0.6	0.5							
	20	1.8	1.5	1.3	1.1	1.0	0.9	0.8	0.7	0.6	0.5						
	30	2.1	1.7	1.5	1.3	1.1	1.0	0.9	0.8	0.7	0.6	0.5					
	40	2.3	1.9	1.6	1.4	1.2	1.1	1.0	0.8	0.7	0.6	0.5					
	60	2.5	2.1	1.8	1.5	1.3	1.2	1.1	0.9	0.8	0.7	0.6	0.5				
	80	2.6	2.2	1.8	1.6	1.4	1.2	1.1	1.0	0.8	0.7	0.6	0.5				
	100	2.7	2.2	1.9	1.6	1.5	1.3	1.2	1.0	0.8	0.8	0.6	0.5				
16	16	1.8	1.5	1.2	1.1	0.9	0.8	0.8	0.6	0.6	0.5						
	20	2.0	1.6	1.4	1.2	1.0	0.9	0.8	0.7	0.6	0.5						
	30	2.3	1.9	1.6	1.4	1.2	1.1	1.0	0.8	0.7	0.6	0.5					
	40	2.5	2.1	1.8	1.5	1.3	1.2	1.1	0.9	0.8	0.7	0.6	0.5				
	60	2.8	2.3	1.9	1.7	1.5	1.3	1.2	1.0	0.9	0.8	0.6	0.5				
	80	3.0	2.4	2.0	1.8	1.6	1.4	1.3	1.1	0.9	0.8	0.7	0.5				
	100	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	0.8	0.7	0.6				
18	20	2.1	1.7	1.5	1.3	1.1	1.0	0.9	0.8	0.7	0.6	0.5					
	30	2.5	2.0	1.7	1.5	1.3	1.2	1.1	0.9	0.8	0.7	0.5					
	40	2.8	2.3	1.9	1.6	1.5	1.3	1.2	1.0	0.9	0.8	0.6	0.5				
	60	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	0.8	0.7	0.6	0.5			
	80	3.3	2.7	2.3	2.0	1.7	1.5	1.4	1.2	1.0	0.9	0.7	0.6	0.5			
	100	3.4	2.8	2.4	2.0	1.8	1.6	1.5	1.2	1.1	0.9	0.7	0.6	0.5			
	120	3.5	2.9	2.4	2.1	1.9	1.6	1.5	1.3	1.1	1.0	0.8	0.6	0.5			
20	20	2.2	1.8	1.5	1.3	1.2	1.0	1.0	0.8	0.7	0.6	0.5					
	30	2.7	2.2	1.8	1.6	1.4	1.3	1.1	1.0	0.8	0.7	0.6	0.5				
	40	3.0	2.4	2.0	1.8	1.6	1.4	1.3	1.1	0.9	0.8	0.7	0.5				
	60	3.3	2.7	2.3	2.0	1.8	1.6	1.4	1.2	1.0	0.9	0.7	0.6	0.5			
	80	3.6	2.9	2.5	2.1	1.9	1.7	1.5	1.3	1.1	1.0	0.8	0.7	0.5			
	100	3.7	3.0	2.6	2.2	2.0	1.8	1.6	1.3	1.2	1.0	0.8	0.7	0.6			
	120	3.8	3.1	2.6	2.3	2.0	1.8	1.6	1.4	1.2	1.0	0.8	0.7	0.6			
25	30	3.0	2.5	2.1	1.8	1.6	1.4	1.3	1.1	0.9	0.8	0.7	0.6				
	40	3.4	2.8	2.4	2.1	1.8	1.6	1.5	1.2	1.1	0.9	0.8	0.6	0.5			
	60	3.9	3.2	2.7	2.4	2.1	1.9	1.7	1.4	1.2	1.1	0.9	0.7	0.6			
	80	4.2	3.5	2.9	2.5	2.2	2.0	1.8	1.5	1.3	1.2	0.9	0.8	0.6	0.5		
	100	4.4	3.6	3.1	2.7	2.4	2.1	1.9	1.6	1.4	1.2	1.0	0.8	0.7	0.5		
	120	4.6	3.8	3.2	2.8	2.4	2.2	2.0	1.7	1.4	1.3	1.0	0.8	0.7	0.5		
	140	4.7	3.9	3.3	2.8	2.5	2.2	2.0	1.7	1.5	1.3	1.0	0.9	0.7	0.5		
30	30	3.3	2.7	2.3	2.0	1.8	1.6	1.4	1.2	1.0	0.9	0.7	0.6	0.5			
	40	3.8	3.1	2.6	2.3	2.0	1.8	1.6	1.4	1.2	1.0	0.8	0.7	0.6			
	60	4.4	3.6	3.1	2.7	2.4	2.1	1.9	1.6	1.4	1.2	1.0	0.8	0.7	0.5		
	80	4.8	4.0	3.4	2.9	2.6	2.3	2.1	1.7	1.5	1.3	1.1	0.9	0.7	0.5		
	100	5.1	4.2	3.6	3.1	2.7	2.4	2.2	1.8	1.6	1.4	1.1	0.9	0.8	0.6	0.5	
	120	5.3	4.4	3.7	3.2	2.8	2.5	2.3	1.9	1.7	1.5	1.2	1.0	0.8	0.6	0.5	
	140	5.5	4.5	3.8	3.3	2.9	2.6	2.3	2.0	1.7	1.5	1.2	1.0	0.8	0.6	0.5	
35	40	4.2	3.4	2.9	2.5	2.2	2.0	1.8	1.5	1.3	1.1	0.9	0.8	0.6	0.5		
	60	4.9	4.0	3.4	2.9	2.6	2.3	2.1	1.8	1.5	1.3	1.1	0.9	0.7	0.6		
	80	5.4	4.4	3.7	3.2	2.9	2.6	2.3	1.9	1.7	1.5	1.2	1.0	0.8	0.6	0.5	
	100		4.7	4.0	3.4	3.1	2.7	2.5	2.1	1.8	1.6	1.3	1.1	0.9	0.6	0.5	
	120		4.9	4.2	3.6	3.2	2.8	2.6	2.2	1.9	1.7	1.3	1.1	0.9	0.7	0.5	
	140		5.1	4.3	3.7	3.3	2.9	2.7	2.2	1.9	1.7	1.4	1.1	0.9	0.7	0.6	
40	40	4.4	3.6	2.4	2.7	2.4	2.1	1.9	1.6	1.4	1.2	1.0	0.8	0.7	0.5		
	60	5.3	4.4	3.7	3.2	2.8	2.5	2.3	1.9	1.7	1.5	1.2	1.0	0.8	0.6	0.5	
	80		4.9	4.1	3.6	3.2	2.8	2.5	2.1	1.8	1.6	1.3	1.1	0.9	0.7	0.5	
	100		5.2	4.4	3.8	3.4	3.0	2.7	2.3	2.0	1.7	1.4	1.2	0.9	0.7	0.6	0.5
	120		5.5	4.6	4.0	3.5	3.2	2.8	2.4	2.1	1.8	1.5	1.2	1.0	0.8	0.6	0.5
	140			4.8	4.1	3.7	3.3	3.0	2.5	2.1	1.9	1.5	1.3	1.0	0.8	0.6	0.5
50	50		4.6	3.8	3.3	3.0	2.6	2.4	2.0	1.7	1.5	1.2	1.0	0.8	0.6	0.5	
	70		5.3	4.5	3.9	3.4	3.1	2.8	2.3	2.0	1.8	1.4	1.2	1.0	0.7	0.6	0.5
	100			5.1	4.4	3.9	3.5	3.2	2.7	2.3	2.0	1.6	1.4	1.1	0.8	0.7	0.5
	140				4.9	4.3	3.9	3.5	2.9	2.5	2.2	1.8	1.5	1.2	0.9	0.7	0.6
	170				5.1	4.6	4.1	3.7	3.1	2.7	2.4	1.9	1.6	1.3	1.0	0.8	0.6
	200				5.3	4.7	4.2	3.8	3.2	2.8	2.4	2.0	1.6	1.3	1.0	0.8	0.6
60	60		5.5	4.6	4.0	3.5	3.2	2.8	2.4	2.1	1.8	1.5	1.2	1.0	0.8	0.6	0.5
	80			5.3	4.6	4.0	3.6	3.3	2.7	2.4	2.1	1.7	1.4	1.1	0.9	0.7	0.5
	100				5.0	4.4	3.9	3.6	3.0	2.6	2.3	1.8	1.5	1.2	0.9	0.8	0.6
	140					5.0	4.4	4.0	3.4	2.9	2.6	2.1	1.7	1.4	1.0	0.8	0.7
	170					5.2	4.7	4.2	3.5	3.1	2.7	2.2	1.8	1.5	1.1	0.9	0.7
	200					5.5	4.9	4.4	3.7	3.2	2.8	2.3	1.9	1.5	1.2	0.9	0.7
80	80				5.3	4.7	4.2	3.8	3.2	2.8	2.4	2.0	1.6	1.3	1.0	0.8	0.6
	140						5.3	4.8	4.1	3.5	3.1	2.5	2.1	1.7	1.3	1.0	0.8
	200							5.4	4.6	3.9	3.5	2.8	2.3	1.9	1.4	1.1	0.9
100	100						5.2	4.8	4.0	3.4	3.0	2.4	2.0	1.6	1.2	1.0	0.8
	150								4.8	4.1	3.7	2.9	2.5	2.0	1.5	1.2	1.0
	200								5.3	4.6	4.1	3.3	2.7	2.2	1.7	1.3	1.1
120	120								4.8	4.1	3.7	2.9	2.5	2.0	1.5	1.2	1.0
	160								5.5	4.7	4.2	3.4	2.8	2.3	1.7	1.4	1.1
	200									5.2	4.6	3.7	3.1	2.5	1.9	1.5	1.2

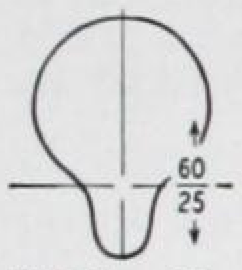
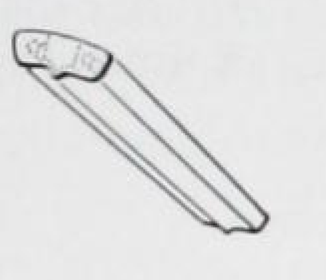
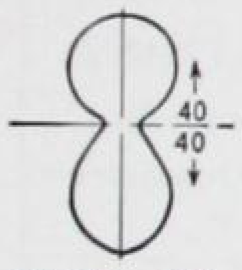
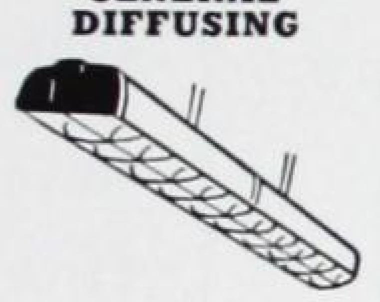
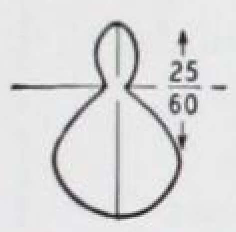
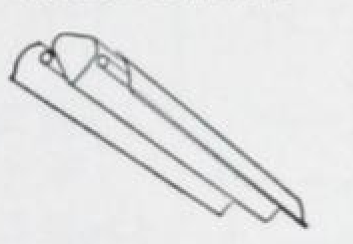
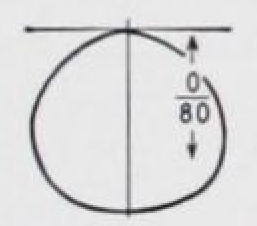
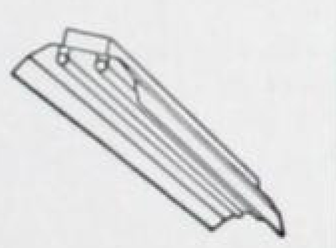
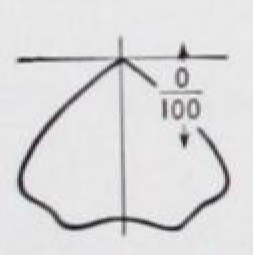
$$\text{Room Ratio} = \frac{W \times L}{H\,(W + L)}$$

Ratio for intermediate dimensions may be calculated.

*Assuming a work-plane 2½' above the floor. The values are given for a limited range of room sizes: use formula in text for other rooms. Since the Coefficients of Utilization are not substantially increased for ratios greater than 5.0 the table has not been extended.

**The mounting height of the luminaire above the floor is used in all cases where the downward component is 40% or more of the total output. Likewise, if the downward component is less than 40%, the ceiling height is used.

TABLE 9 — COEFFICIENTS OF UTILIZATION FOR SIX GENERAL TYPES OF LUMINAIRES

TYPICAL DISTRIBUTION	LUMINAIRE	Ceiling	80%			70%			50%			30%			80%			70%		
		Walls	50%	30%	10%	50%	30%	10%	50%	30%	10%	50%	30%	10%	50%	30%	10%	50%	30%	10%
		Floor	10%			10%			10%			10%			30%			30%		
		Room Ratio																		
 M. F. =.70	INDIRECT* 	0.6	.27	.21	.16	.24	.19	.14	.17	.14	.11	.12	.09	.07	.28	.22	.16	.25	.20	.14
		0.8	.34	.28	.22	.30	.25	.20	.22	.18	.15	.15	.12	.09	.35	.27	.23	.32	.26	.20
		1.0	.39	.33	.28	.35	.30	.25	.26	.22	.18	.17	.14	.12	.42	.35	.28	.37	.31	.25
		1.25	.45	.39	.33	.40	.34	.29	.30	.26	.22	.20	.17	.14	.48	.41	.34	.42	.36	.30
		1.5	.49	.43	.38	.43	.38	.33	.32	.28	.24	.22	.19	.16	.52	.45	.38	.47	.40	.34
		2.0	.55	.49	.44	.48	.43	.39	.36	.32	.29	.24	.22	.19	.60	.52	.46	.53	.46	.41
		2.5	.58	.53	.48	.52	.47	.43	.38	.35	.32	.26	.23	.21	.65	.58	.52	.57	.51	.45
		3.0	.61	.56	.52	.54	.50	.46	.40	.37	.34	.27	.25	.23	.69	.62	.56	.60	.54	.49
		4.0	.65	.61	.57	.57	.54	.50	.43	.40	.37	.28	.26	.25	.75	.68	.62	.64	.59	55
		5.0	.68	.64	.61	.59	.56	.53	.44	.42	.39	.29	.27	.26	.78	.72	.67	.67	.63	.59
 M. F. =.65	SEMI-INDIRECT 	0.6	.24	.19	.15	.22	.17	.13	.17	.14	.11	.13	.11	.08	.24	.19	.15	.22	.18	.14
		0.8	.30	.25	.20	.27	.23	.19	.22	.18	.15	17	.14	.12	.31	.26	.21	.28	.23	.19
		1.0	.35	.30	.25	.32	.27	.23	.26	.22	.19	.20	.17	.14	.37	.31	.26	.33	.28	.24
		1.25	.40	.35	.30	.36	.32	.28	.29	.26	.22	.22	.20	.18	.42	.36	.31	.38	.33	.28
		1.5	.44	.38	.34	.40	.35	.31	.32	.28	.25	.24	.22	.20	.47	.40	.35	.43	.37	.32
		2.0	.49	.44	.40	.44	.40	.36	.36	.32	.29	.27	.25	.23	.53	.47	.41	.48	.43	.38
		2.5	.52	.48	.44	.48	.44	.40	.38	.35	.32	.29	.27	.25	.57	.51	.46	.52	.47	.42
		3.0	.55	.50	.47	.50	.46	.42	.40	.37	.34	.30	.28	.27	.61	.55	.50	.55	.50	.46
		4.0	.58	.54	.51	.53	.49	.46	.43	.40	.37	.32	.30	.29	.65	.60	.55	.59	.54	.50
		5.0	.60	.57	.54	.55	.52	.49	.45	.42	.39	.34	.32	.31	.68	.63	.59	.61	.57	.54
 M. F. =.70	GENERAL DIFFUSING 	0.6	.26	.21	.18	.25	.21	.17	.23	.19	.16	.20	.17	.15	.27	.22	.18	.26	.21	.17
		0.8	.32	.27	.23	.31	.26	.22	.28	.24	.21	.25	.22	.19	.34	.28	.23	.32	.27	.22
		1.0	.38	.33	.29	.36	.32	.28	.33	.29	.26	.29	.26	.23	.40	.34	.29	.38	.32	.28
		1.25	.43	.38	.34	.41	.36	.33	.37	.33	.30	.33	.30	.27	.46	.40	.34	.43	.38	.33
		1.5	.47	.42	.38	.45	.40	.36	.40	.36	.33	.35	.32	.30	.50	.44	.39	.48	.42	.37
		2.0	.53	.48	.44	.50	.46	.42	.44	.41	.38	.39	.36	.34	.57	.51	.46	.54	.48	.44
		2.5	.56	.52	.48	.53	.49	.46	.47	.44	.41	.41	.39	.37	.62	.56	.50	.58	.53	.48
		3.0	.59	.55	.51	.55	.52	.49	.49	.46	.44	.43	.41	.39	.65	.59	.54	.61	.55	.52
		4.0	.62	.59	.56	.58	.55	.53	.52	.49	.47	.45	.43	.42	.70	.65	60	.65	.61	.57
		5.0	.64	.61	.59	.61	.58	.55	.54	.51	.49	.46	.45	.44	.73	.68	64	.68	.64	.61
 M. F. =.70	SEMI-DIRECT 	0.6	.34	.28	.24	.33	.28	.24	.31	.26	.24	.30	.25	.22	.35	.29	.24	.34	.28	.24
		0.8	.42	.36	.32	.40	.35	.31	.38	.33	.30	.36	.32	.29	.43	.37	.32	.42	.36	.31
		1.0	.48	.42	.38	.47	.41	.37	.44	.39	.36	.41	.37	.34	.50	.43	.38	.48	.42	.38
		1.25	.54	.48	.44	.52	.47	.43	.49	.45	.41	.46	.42	.39	.57	.50	.45	.55	.49	.44
		1.5	.58	.53	.48	.56	.51	.47	.53	.49	.45	.49	.46	.43	.62	.55	.50	.60	.54	.49
		2.0	.64	.59	.55	.62	.57	.54	.58	.54	.51	.54	.51	.48	.69	.62	.57	.66	.61	.56
		2.5	.67	.63	.59	.65	.61	.58	.60	.57	.54	.56	.54	.52	.74	.68	.62	.71	.65	.60
		3.0	.70	.66	.62	.68	.64	.61	.63	.60	.57	.58	.56	.54	.78	.72	.67	.74	.68	.64
		4.0	.73	.70	.67	.70	.67	.65	.66	.63	.61	.61	.59	.57	.82	.77	.73	.78	.75	.70
		5.0	.75	.72	.70	.72	.70	.68	.68	.65	.63	.62	.61	.60	.86	.81	.77	.81	.78	.74
 M. F. =.65	DIRECT 	0.6	.34	.28	.24	.34	.28	.23	.33	.27	.24	.32	.27	.23	.35	.28	.24	.35	.28	.23
		0.8	.43	.36	.31	.42	.36	.31	.41	.35	.31	.40	.35	.31	.44	.36	.31	.44	.36	.31
		1.0	.49	.42	.38	.48	.42	.38	.47	.42	.37	.46	.41	.37	.51	.43	.38	.50	.42	.38
		1.25	.55	.49	.44	.55	.48	.44	.53	.48	.44	.52	.47	.44	.58	.55	.45	.57	.50	.45
		1.5	.60	.54	.49	.59	.53	.49	.57	.52	.48	.56	.52	.48	.64	.56	.50	.62	.55	.50
		2.0	.65	.60	.56	.64	.60	.55	.63	.59	.55	.61	.58	.55	.71	.64	.58	.69	.63	.58
		2.5	.69	.64	.60	.68	.64	.60	.66	.63	.59	.65	.62	.59	.76	.69	.64	.74	.68	.63
		3.0	.72	.67	.64	.71	.67	.63	.69	.66	.63	.67	.65	.62	.80	.74	.68	.78	.72	.67
		4.0	.76	.72	.69	.75	.71	.69	.73	.70	.68	.71	.69	.67	.85	.80	.75	.83	.78	.74
		5.0	.78	.75	.72	.77	.74	.72	.75	.73	.71	.74	.72	.70	.89	.85	.81	.87	.83	.79
 M. F. =.70	DIRECT* 	0.6	.53	.46	.42	.53	.46	.42	.52	.46	.42	.51	.46	.42	.54	.47	.42	.54	.46	.42
		0.8	.64	.57	.52	.63	.57	.52	.62	.56	.52	.61	.56	.52	.66	.58	.53	.66	.58	.53
		1.0	.72	.65	.60	.71	.65	.60	.70	.64	.60	.68	.64	.60	.75	.67	.61	.74	.66	.61
		1.25	.78	.72	.68	.78	.72	.68	.76	.71	.68	.75	.70	.67	.83	.75	.69	.82	.74	.69
		1.5	.83	.77	.73	.82	.77	.73	.81	.76	.72	.80	.76	.72	.89	.81	.75	.88	.80	.75
		2.0	.89	.84	.80	.88	.84	.80	.87	.83	.80	.85	.82	.79	.97	.90	.84	.95	.89	.83
		2.5	.93	.88	.85	.92	.88	.84	.90	.86	.84	.88	.86	.83	1.02	.96	.90	1.00	.94	.89
		3.0	.95	.98	.88	.94	.91	.88	.92	.90	.87	.91	.88	.86	1.06	1.00	.95	1.04	.98	.94
		4.0	.99	.95	.93	.97	.94	.92	.95	.93	.91	.94	.92	.90	1.12	1.06	1.01	1.09	1.04	1.00
		5.0	1.01	.98	.96	1.00	.97	.95	.98	.96	.94	.96	.94	.92	1.15	1.10	1.06	1.12	1.08	1.04

*Coefficients of Utilization are based on the lumen output of reflectorized lamps. Coefficients greater than 1.0 are the result of interreflections of light by the floor, walls, and other surfaces. This builds up the footcandle level beyond the initial lamp lumens per sq. ft. of work-plane area.

TABLE 9 — COEFFICIENTS OF UTILIZATION for two types of LUMINOUS CEILINGS *

Description: Acrylic plastic corrugated sheets: transmittance = .53; reflectance = .39; cavity efficiency = .68; diffusing plastic wall to wall.

Description: Vinyl plastic corrugated sheets: transmittance = .45; reflectance = .45; cavity efficiency = .62; diffusing plastic wall to wall.

WALLS	50%	30%	10%	50%	30%	10%	50%	30%	10%	50%	30%	10%
FLOOR	10%			30%			10%			30%		
Room Ratio												
0.6	.27	.22	.18	.28	.22	.18	.23	.19	.16	.24	.20	.16
0.8	.33	.28	.25	.36	.29	.24	.29	.24	.22	.29	.25	.22
1.0	.38	.34	.30	.42	.34	.30	.33	.29	.26	.34	.30	.27
1.25	.43	.38	.34	.48	.40	.35	.38	.34	.31	.40	.36	.32
1.5	.46	.42	.38	.52	.45	.40	.42	.38	.35	.44	.40	.36
2.0	.51	.47	.43	.58	.51	.47	.48	.43	.40	.51	.47	.43
2.5	.55	.51	.47	.61	.55	.51	.51	.47	.44	.54	.51	.48
3.0	.58	.54	.50	.64	.58	.55	.54	.49	.47	.57	.54	.51
4.0	.61	.58	.54	.68	.62	.59	.59	.53	.50	.60	.58	.55
5.0	.64	.60	.57	.71	.65	.62	.59	.55	.52	.62	.60	.58

The coefficients of utilization in this table were derived by calculation. Cavity efficiency is the fraction of lamp lumens emitted by the luminous ceiling surface. Accumulated heat in a cavity may account for coefficients being reduced materially. Allowance should be made for this condition in the design.

*Data from "Measured Illumination Data for Luminous Ceilings," A. H. Russell and R. D. Churchill, Illuminating Engineering, 1956.

GENERAL LIGHTING DESIGN PROCEDURE

The Lumen Method Summary shows the principal steps in designing fluorescent and filament lighting systems. The first eight steps are identical for both systems. The steps are determinations of:

1. Characteristics of Room, Type of Interior, Seeing Task. The dimensions of the room are determined, reflectances of walls, ceiling, and floor selected or measured, and the limits of "height in the clear" noted. Decorative factors and type of work or display or function of the space are recorded. The seeing task determines—

2. Horizontal Footcandle Level. Published tables of recommended values (average in service) are of considerable assistance. See Lamp Div. Bulletin "Levels of Illumination", I.E.S. American Recommended Practice bulletins, and I.E.S. Lighting Handbook.

3. Type of Luminaire. The selection of the luminaire is based upon the size and type of interior, the seeing tasks, cost, and other factors.

4. Maximum Spacing. Values of allowable spacing between luminaires and spacing from end rows to walls are found in Table 7.

5. Room Ratio. See Table 8.

6. Maintenance Factor. Suggested maintenance factors are shown in tables of Coefficients of Utilization. Local conditions, however, may alter the recommended values considerably.

7. Coefficient of Utilization. Calculated values of the coefficient of utilization of the luminaire selected may be found in the manufacturer's catalog, in tables as in G. E. Lamp Division bulletins, or calculated by the method outlined.

8. Total Lamp Lumens Required. This value is found from the formula:

$$\text{Tot. Lumens Required} = \frac{\text{Footcandles} \times \text{Area}}{\text{C.U.} \times \text{Maintenance Factor}}$$

9. Location, Number and Size of Luminaires.
Fluorescent Lighting System

A representative luminaire having been chosen, the Number of Lamps and the Lumens per Lamp are multiplied to find the Lumens per luminaire: Lm/Lc.

The number of luminaires required is found by dividing LmR (from 8) by Lm/Le.

$$\frac{\text{LmR}}{\text{Lm/Le}} = \text{N}$$

The units (N) are arranged in rows or otherwise to make a symmetrical layout, not exceeding the maximum spacing and distance to walls. In practice it may be necessary to add a few units to the number (N) for symmetry, or to choose a luminaire with more or less lamps or lamps of other output.

Filament Lighting System

A representative luminaire is chosen and the designer makes a layout in accordance with the allowable spacing limits recorded in (4).

From the layout, the proposed number of luminaires (N) is counted. By dividing the Lumens Required (LmR) from (8) by this Number (N) in the layout, a required value of "Lumens per luminaire" is secured:

$$\frac{\text{LmR}}{\text{N}} = \text{Lm/Le}$$

This value is used to find the lamp most nearly supplying the required lumens. Actually, some rearrangement of spacing and lamp size is usually necessary.

The Lumen Method is summarized in 9 steps as follows:

1. *Characteristics of Room*

Length..................ft

Width..................ft

Area..................sq. ft.

Reflectances

Ceiling..................%

Walls..................%

Floor..................%

2. *Footcandle Level*.......Fc

3. *Luminaire Type*...............

....

4. *Spacing of Luminaires*

Between rows...............ft.

Distance to walls...........ft.

5. *Room Ratio*....................

6. *Maintenance Factor*............

7. *Coefficient of Utilization*............

8. *Lumens Required* $= \dfrac{Fc \times Area}{CU \times MF}$

9. *Location, Number and Size of Luminaires*

Fluorescent Lighting System

A. Lumens/Luminaire (Lm/Le) = No. of lamps/Le × Lm/Lp.

B. No. of Luminaires (N) $= \dfrac{\text{Lumens Required (Step 8)}}{\text{Lm/Le}}$

C. Make layout using Table 7 as a guide and N from 9B

D. Actual total Lamp Lumens = N from Step 9C × Lm/Le

E. Actual Av. Fc $= \dfrac{\text{Fc (Step 2)} \times \text{Lamp Lumens 9D}}{\text{Lumens Required (Step 8)}}$

F. Initial Fc = Actual Av. Footcandles ÷ MF

Filament Lighting System

A. Make layout using Table 7 as a guide and determine the number (N) of luminaires

B. Lumens Require/Luminaire (Lm/Le) = Lumens

C. From schedules, find nearest lamp:
...............W...............Lm

D. Actual Total Lamp Lumens = N × Lm/Lp

E. Actual Av. Fc $= \dfrac{\text{Fc (Step 2)} \times \text{Actual Tot. Lp. Lumens}}{\text{Lumens Required (Step 8)}}$

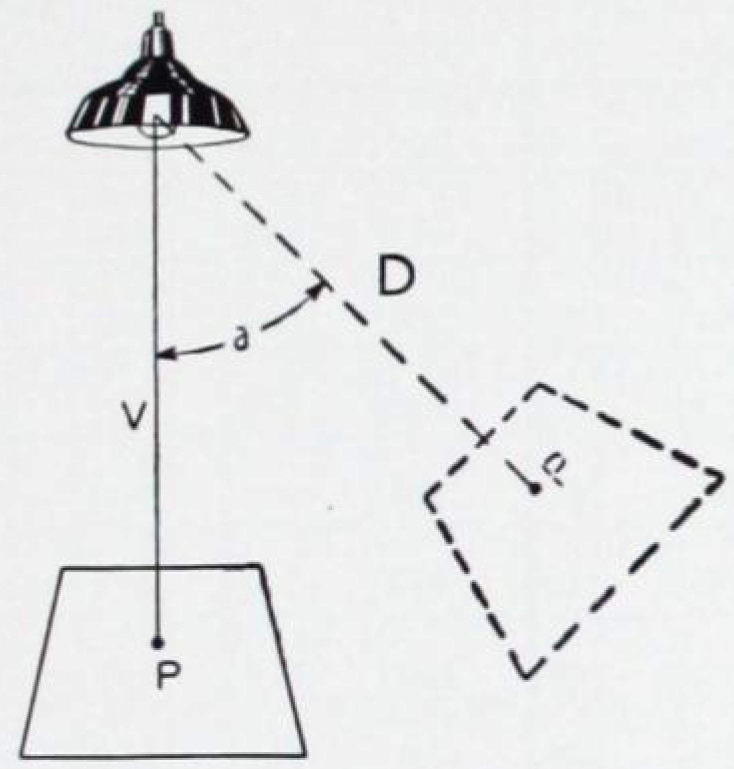
F. Initial Fc = Actual Av. Footcandles ÷ MF

ABBREVIATIONS	
Fc	**= Footcandles**
MF	**= Maintenance factor**
CU	**= Coeff. of Utilization**
Lm	**= Lumen(s)**
Le	**= Luminaire**
Lp	**= Lamp**
W	**= Watts**
LmR	**= Lumens Required**
N	**= No. of Luminaires**

SUPPLEMENTARY LIGHTING

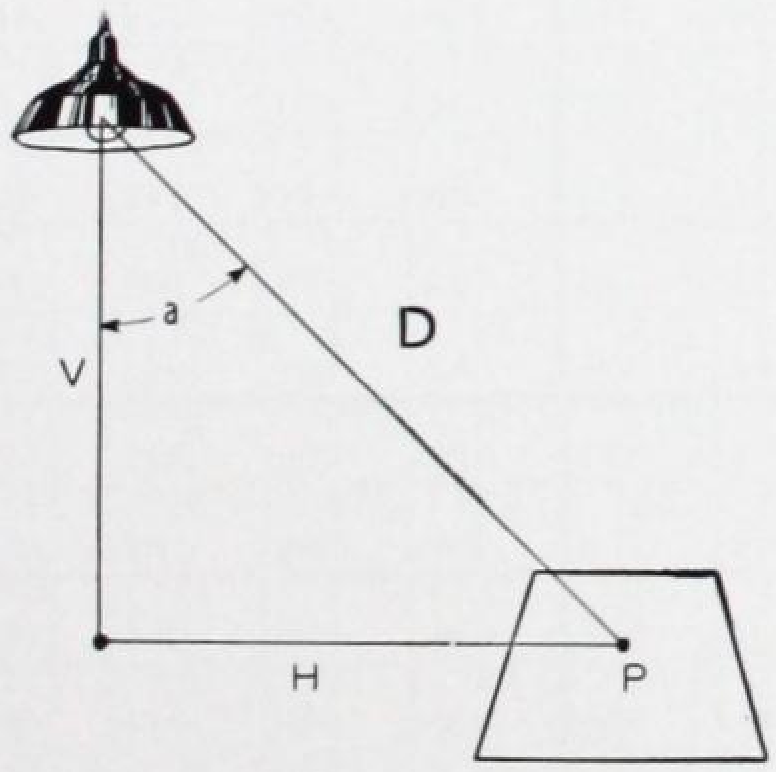
THE POINT-BY-POINT METHOD

The Point-by-Point method of lighting calculation is employed when single luminaires are used or when special types of equipment not commonly adapted for general lighting systems are specified. The system facilitates making quick estimates of footcandle results in the application of auxiliary spotlights and floodlights. This method is based on the application of the inverse square law (page 6) to data obtained from the candlepower distribution curve of the luminaire. The footcandles are computed by use of one of the three following formulas, depending on the point location.



A. *When the point is in a plane normal to the beam,* the formula is:

$$\text{Footcandles} = \frac{\text{CP (candlepower)}}{V^2 \text{ (Distance in feet)}}$$



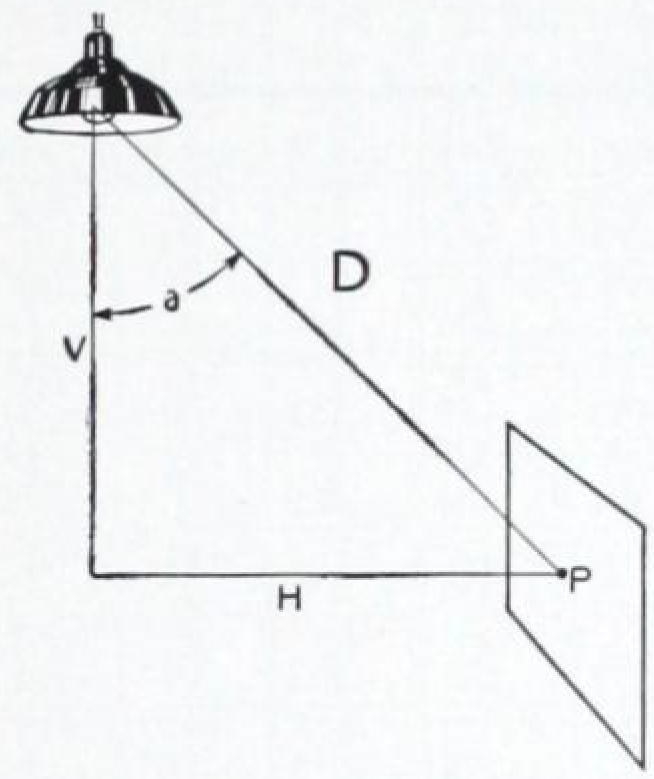
B. *When the point is on a horizontal plane at a distance H,* (see sketch) the formula is:

$$\text{Horizontal Footcandles} = \frac{\text{CP x Cosine of Angle } a}{(V^2 + H^2)}$$

$V^2 + H^2$ is equal to D^2; D is the distance from the source to the point P. (Note: When $H = 0$, $\cos = 1.0$, and $Fc = \frac{CP}{V^2}$ as in "A.")

(Cosines of angles are given on page 6.)

In Table 10A, the footcandle levels on the *horizontal* plane have been calculated for a source of 100 cp for a wide range of mounting heights (V) and horizontal distances from the luminaire (H). For higher mounting heights or projection distances encountered in the use of powerful projectors, the values have been computed for 100,000 cp. Given also is the angle in degrees so that at any conventional height and distance, the actual candlepower for that particular angle may be taken from the distribution curve of the unit. By dividing the actual candlepower at this angle (CP*a*) by 100, then multiplying by the footcandles produced per hundred candlepower as given in the table, the resultant horizontal footcandles at the point may be obtained. When the 100,000 cp part of the table is used, the actual candlepower is divided by 100,000, then multiplied by the Fc value per 100,000 cp from the table. The result is the horizontal footcandles at the point.



C. *When the point is on a vertical plane,* the formula is:

$$\text{Vertical Footcandles} = \frac{\text{CP x cos } (90° - a)}{(V^2 + H^2)}$$

In Table 10B, the footcandle levels on the *vertical* plane are calculated for a source of 100 cp for the same range of vertical heights and horizontal distances as in Table 10A. To find the vertical footcandle value, the distances H and V locate the angle (upper figure) and the actual candlepower value is obtained from the candlepower distribution curve of the unit at this angle. By dividing this cp value by 100 and multiplying it by the footcandle value in the table, the actual vertical footcandle level at the point is obtained. Similar values for a 100,000 cp source are also included. When this section of the table is used, it is necessary to divide the distribution curve cp value by 100,000, then multiply it by the footcandle value for that angle in the table.

These tables can be utilized in the calculation of the distribution of ultraviolet energy from sunlamp systems by substituting for the 100 cp an erythemal equivalent such as 10 E-vitons per steradian. The erythemal level at the point is numerically equal to 1/10 that of the Fc level found in the table.

Similar determinations of germicidal installations are facilitated by using the table. Substituting 1000 microwatts per steradian for 100 cp in the table, the numerical point values would be ten times the Fc values in the table.

TABLE No. 10A

Upper Figures — Angle Between Light Ray and Vertical
Lower Figures — Footcandles on a HORIZONTAL Plane Produced by a Source of 100 Candlepower

V = VERTICAL HEIGHT OF LIGHT SOURCE ABOVE SURFACE TO BE LIGHTED—FEET	H-HORIZONTAL DISTANCE FROM UNIT—FEET															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
4	0° 0′ 6.250	14° 5.707	27° 4.472	37° 3.200	45° 2.210	51° 1.524	56° 1.066	60° .764	63° .559	66° .419	68° .320	70° .249	72° .198	73° .159	74° .130	75° .107
5	0° 0′ 4.000	11° 3.771	22° 3.202	31° 2.522	39° 1.904	45° 1.414	50° 1.050	54° .785	58° .595	61° .458	63° .358	66° .283	67° .228	69° .185	70° .152	72° .126
6	0° 0′ 2.778	9° 2.673	18° 2.372	27° 1.987	34° 1.600	40° 1.260	45° .982	49° .766	53° .600	56° .474	59° .378	61° .305	63° .249	66° .205	67° .170	68° .142
7	0° 0′ 2.041	8° 1.980	16° 1.814	23° 1.585	30° 1.336	36° 1.100	41° .893	45° .722	49° .583	52° .473	55° .385	58° .316	60° .261	62° .218	63° .183	65° .154
8	0° 0′ 1.563	7° 1.527	14° 1.427	21° 1.283	27° 1.118	32° .953	37° .800	41° .666	45° .552	48° .458	51° .381	54° .318	56° .267	58° .225	60° .191	62° .163
9	0° 0′ 1.235	6° 1.212	13° 1.148	18° 1.054	24° .943	29° .825	34° .711	38° .607	42° .515	45° .437	48° .370	51° .314	53° .267	55° .228	57° .196	59° .168
10	0° 0′ 1.000	5° 43′ .985	11° .943	17° .879	22° .801	27° .716	31° .631	35° .550	39° .476	42° .411	45° .354	48° .305	50° .263	52° .227	54° .196	56° .171
11	0° 0′ .826	5° 12′ .816	10° .787	15° .742	20° .686	24° .623	29° .559	32° .496	36° .437	39° .383	42° .335	45° .292	48° .255	50° .223	52° .195	54° .171
12	0° 0′ .694	4° 46′ .687	9° .668	14° .634	18° .593	23° .546	27° .497	30° .448	34° .400	37° .356	40° .315	43° .278	45° .246	47° .217	49° .191	51° .169
13	0° 0′ .592	4° 24′ .587	9° .571	13° .547	17° .517	21° .481	25° .447	28° .404	32° .366	35° .329	38° .295	40° .263	43° .235	45° .200	47° .187	49° .166
14	0° 0′ .510	4° 5′ .506	8° .495	12° .477	16° .454	20° .426	23° .396	27° .365	30° .334	33° .304	36° .275	38° .248	41° .223	43° .201	45° .180	47° .162
15	0° 0′ .444	3° 49′ .442	8° .433	11° .419	15° .401	18° .380	22° .356	25° .331	28° .305	31° .280	34° .256	36° .233	39° .212	41° .192	43° .174	45° .157
16	0° 0′ .391	3° 35′ .388	7° .382	11° .371	14° .357	17° .339	21° .321	24° .300	27° .280	29° .259	32° .238	35° .219	37° .200	39° .183	41° .167	43° .152
17	0° 0′ .346	3° 22′ .344	7° .339	10° .331	13° .319	16° .306	19° .290	22° .274	25° .256	28° .239	30° .222	33° .205	35° .189	37° .174	39° .159	41° .146
18	0° 0′ .309	3° 11′ .307	6° .303	9° .297	13° .287	16° .276	18° .264	21° .250	24° .236	27° .221	29° .206	31° .192	34° .178	36° .165	38° .152	40° .140
19	0° 0′ .277	3° 1′ .276	6° .273	9° .267	12° .260	15° .251	18° .240	20° .229	23° .217	25° .205	28° .192	30° .180	32° .167	34° .156	36° .145	38° .134
20	0° 0′ .250	2° 51′ .249	5° 43′ .246	9° .242	11° .236	14° .228	17° .219	19° .210	22° .200	24° .190	27° .179	29° .168	31° .158	33° .147	35° .137	37° .128
21	0° 0′ .227	2° 44′ .226	5° 26′ .224	8° .220	11° .215	13° .210	16° .201	18° .194	21° .185	23° .176	25° .167	28° .158	30° .144	32° .139	34° .131	36° .122
22	0° 0′ .207	2° 36′ .206	5° 10′ .205	8° .201	10° .196	13° .192	15° .185	18° .179	20° .171	22° .164	25° .155	27° .148	29° .140	31° .132	33° .124	34° .114
23	0° 0′ .189	2° 29′ .189	4° 58′ .187	7° .184	10° .181	12° .176	15° .171	17° .165	19° .159	21° .153	24° .146	26° .139	28° .132	29° .125	31° .118	33° .111
24	0° 0′ .174	2° 23′ .173	4° 45′ .172	7° .170	10° .166	12° .163	14° .158	16° .154	18° .148	21° .143	23° .137	25° .130	27° .124	28° .118	30° .112	32° .106
25	0° 0′ .160	2° 17′ .160	4° 34′ .158	7° .157	9° .154	11° .151	14° .147	16° .143	18° .138	20° .133	22° .128	24° .123	26° .117	27° .112	29° .106	31° .101
27	0° 0′ .137	2° 7′ .137	4° 14′ .136	6° .135	8° .133	10° .130	12° .128	15° .124	17° .121	18° .117	20° .113	22° .109	24° .105	26° .100	27° .096	29° .092
30	0° 0′ .111	1° 54′ .111	3° 50′ .111	5° 43′ .109	8° .108	9° .107	11° .105	13° .103	15° .100	17° .098	18° .095	20° .092	22° .089	23° .086	25° .083	27° .080
33	0° 0′ .092	1° 44′ .092	3° 28′ .091	5° 12′ .091	7° .090	9° .089	10° .087	12° .086	14° .084	15° .082	17° .080	18° .078	20° .076	22° .074	23° .072	24° .069
36	0° 0′ .077	1° 36′ .077	3° 11′ .077	4° 46′ .076	6° .076	8° .075	9° .074	11° .073	13° .072	14° .070	16° .069	17° .067	18° .066	20° .064	21° .062	23° .061
40	0° 0′ .063	1° 26′ .062	2° 52′ .062	4° 17′ .062	5° 43′ .062	7° .061	9° .060	10° .060	11° .059	13° .058	14° .057	15° .056	17° .055	18° .054	19° .053	21° .051
45	0° 0′ .049	1° 16′ .049	2° 33′ .049	3° 49′ .049	5° 5′ .049	6° .049	8° .048	9° .048	10° .047	11° .047	13° .046	14° .045	15° .045	16° .044	17° .043	18° .042
50	0° 0′ .040	1° 9′ .040	2° 17′ .040	3° 26′ .040	4° 34′ .040	5° 43′ .039	7° .039	8° .039	9° .039	10° .038	11° .038	12° .037	14° .037	15° .036	16° .036	16° .035
55	0° 0′ .033	1° 2′ .033	2° 5′ .033	3° 7′ .033	4° 10′ .033	5° 9′ .033	6° .032	7° .032	8° .032	9° .032	10° .032	11° .031	12° .031	13° .031	14° .030	15° .030
60	0° 0′ .028	0° 57′ .028	1° 55′ .028	2° 52′ .028	3° 50′ .028	4° 46′ .027	5° 43′ .027	7° .027	8° .027	9° .027	9° .027	10° .026	11° .026	12° .026	13° .026	14° .025
70	0° 0′ .020	0° 49′ .020	1° 38′ .020	2° 34′ .020	3° 16′ .020	4° 5′ .020	4° 54′ .020	5° 43′ .020	7° .020	7° .020	8° .020	9° .020	10° .020	11° .019	11° .019	12° .019
	100.000 CANDLEPOWER SOURCE															
80	0° 0′ 15.625	0° 43′ 15.616	1° 26′ 15.610	2° 9′ 15.592	2° 52′ 15.567	3° 35′ 15.534	4° 17′ 15.494	5° 0′ 15.447	5° 43′ 15.393	6° 15.345	7° 15.270	8° 15.186	9° 15.093	9° 15.036	10° 14.930	11° 14.817
100	0° 0′ 10.000	0° 34′ 9.999	1° 9′ 9.994	1° 43′ 9.987	2° 17′ 9.976	2° 52′ 9.963	3° 26′ 9.946	4° 0′ 9.927	4° 34′ 9.905	5° 9′ 9.880	5° 43′ 9.852	6° 9.826	7° 9.785	7° 9.761	8° 9.712	9° 9.660
125	0° 0′ 6.400	0° 28′ 6.399	0° 55′ 6.398	1° 22′ 6.395	1° 50′ 6.390	2° 17′ 6.385	2° 45′ 6.378	3° 12′ 6.370	3° 40′ 6.361	4° 7′ 6.351	4° 34′ 6.339	5° 2′ 6.326	5° 29′ 6.313	6° 6.297	6° 6.286	7° 6.262
150	0° 0′ 4.444	0° 23′ 4.444	0° 46′ 4.443	1° 9′ 4.442	1° 32′ 4.440	1° 55′ 4.437	2° 17′ 4.434	2° 40′ 4.430	3° 2′ 4.421	3° 26′ 4.416	3° 49′ 4.415	4° 11′ 4.409	4° 34′ 4.402	4° 57′ 4.395	5° 20′ 4.387	5° 43′ 4.379
175	0° 0′ 3.265	0° 20′ 3.265	0° 39′ 3.265	0° 59′ 3.264	1° 19′ 3.263	1° 38′ 3.261	1° 58′ 3.260	2° 17′ 3.258	2° 37′ 3.255	2° 57′ 3.252	3° 16′ 3.249	3° 36′ 3.246	3° 55′ 3.242	4° 15′ 3.238	4° 34′ 3.234	4° 54′ 3.230
200	0° 0′ 2.500	0° 17′ 2.500	0° 34′ 2.500	0° 52′ 2.499	1° 9′ 2.499	1° 26′ 2.498	1° 43′ 2.497	2° 0′ 2.495	2° 17′ 2.494	2° 35′ 2.492	2° 52′ 2.490	3° 9′ 2.489	3° 26′ 2.437	3° 43′ 2.484	4° 0′ 2.482	4° 17′ 2.479

TABLE No. 10A

Upper Figures — Angle Between Light Ray and Vertical
Lower Figures — Footcandles on a HORIZONTAL Plane Produced by a Source of 100 Candlepower

H—HORIZONTAL DISTANCE FROM UNIT—FEET

V = VERTICAL HEIGHT OF LIGHT SOURCE ABOVE SURFACE TO BE LIGHTED—FEET

V	16	17	18	19	20	22	24	26	28	30	32	34	36	40	44	48	52
4	76° .090	77° .075	78° .064	78° .055	79° .047	80° .037	81° .028	81° .022	82° .018	82° .015	83° .012	83° .010	84° .008	84° .006	85° .005	85° .004	86° .003
5	73° .106	74° .090	74° .077	75° .066	76° .057	77° .044	78° .034	79° .027	80° .022	81° .017	81° .015	82° .012	82° .010	83° .008	84° .006	84° .005	85° .004
6	69° .120	71° .102	71° .088	72° .076	73° .066	75° .051	76° .040	77° .032	78° .026	79° .021	79° .017	80° .015	80° .012	81° .009	82° .007	83° .005	83° .004
7	66° .131	68° .113	69° .097	70° .084	71° .074	72° .057	74° .045	75° .036	76° .029	77° .024	78° .020	78° .017	79° .014	80° .010	81° .008	82° .006	82° .005
8	63° .140	65° .121	66° .105	67° .091	68° .080	70° .063	72° .050	73° .040	74° .032	75° .026	76° .022	77° .019	77° .016	79° .012	80° .009	81° .007	81° .006
9	61° .146	62° .126	63° .110	65° .097	66° .085	68° .067	69° .053	71° .043	72° .035	73° .029	74° .025	75° .021	76° .018	77° .013	78° .010	79° .008	80° .006
10	58° .149	60° .130	61° .115	62° .101	63° .089	66° .071	67° .057	69° .046	70° .038	72° .032	73° .027	74° .022	74° .019	76° .014	77° .011	78° .009	79° .007
11	56° .150	57° .132	59° .117	60° .104	61° .092	63° .074	65° .060	67° .049	69° .040	70° .034	71° .028	72° .024	73° .021	75° .015	76° .012	77° .009	78° .007
12	53° .150	55° .133	56° .119	58° .106	59° .094	61° .076	63° .062	65° .051	67° .043	68° .036	69° .030	71° .026	72° .022	73° .017	75° .013	76° .010	77° .008
13	51° .148	53° .133	54° .119	56° .106	57° .096	59° .078	62° .064	63° .053	65° .044	67° .037	68° .032	69° .027	70° .023	72° .017	74° .013	75° .011	76° .008
14	49° .146	51° .131	52° .118	54° .107	55° .096	58° .079	60° .065	62° .054	63° .046	65° .039	66° .033	68° .028	69° .024	71° .018	72° .014	74° .011	75° .009
15	47° .142	49° .129	50° .117	52° .106	53° .096	56° .079	58° .066	60° .055	62° .047	63° .040	65° .034	66° .029	67° .025	69° .019	71° .015	73° .012	74° .009
16	45° .138	47° .126	48° .115	50° .105	51° .095	54° .080	56° .067	58° .056	60° .048	62° .041	63° .035	65° .030	66° .026	68° .020	70° .016	72° .012	73° .010
17	43° .134	45° .122	47° .112	48° .103	50° .094	52° .079	55° .069	57° .057	59° .048	60° .042	62° .036	63° .031	65° .027	67° .021	69° .016	71° .013	72° .010
18	42° .129	43° .119	45° .109	47° .100	48° .092	51° .079	53° .067	55° .057	57° .049	59° .042	61° .036	62° .032	63° .028	66° .021	68° .017	69° .013	71° .011
19	40° .124	42° .115	43° .106	45° .098	46° .090	49° .077	52° .066	54° .057	56° .049	58° .042	59° .037	61° .032	62° .028	65° .022	67° .017	68° .014	70° .011
20	39° .119	40° .111	42° .103	44° .095	45° .088	48° .076	50° .066	52° .057	54° .049	56° .043	58° .037	60° .033	61° .029	63° .022	66° .018	67° .014	69° .012
21	37° .114	39° .107	41° .099	42° .092	44° .086	46° .075	49° .065	51° .056	53° .049	55° .043	57° .038	58° .033	60° .029	62° .023	64° .018	66° .015	68° .012
22	36° .109	38° .102	39° .096	41° .091	42° .084	45° .073	47° .064	50° .056	52° .049	54° .043	55° .038	57° .033	59° .029	61° .023	63° .019	65° .015	67° .012
23	35° .105	36° .098	38° .092	40° .087	41° .081	44° .071	46° .063	49° .055	51° .049	53° .043	54° .038	56° .033	57° .030	60° .023	62° .019	64° .015	66° .013
24	34° .100	35° .094	37° .089	38° .084	40° .079	43° .070	45° .061	47° .054	49° .048	51° .042	53° .037	55° .033	56° .030	59° .024	61° .019	63° .016	65° .013
25	33° .096	34° .091	36° .086	37° .081	39° .076	41° .068	44° .060	46° .053	48° .047	50° .042	52° .037	54° .033	55° .030	58° .024	60° .019	62° .016	64° .013
27	31° .087	32° .083	34° .079	35° .075	37° .071	39° .064	42° .057	44° .051	46° .046	48° .041	50° .037	52° .033	53° .030	56° .024	58° .020	61° .016	63° .013
30	28° .077	30° .073	31° .070	32° .067	34° .064	36° .058	39° .053	41° .048	43° .043	45° .039	47° .036	49° .032	50° .029	53° .024	56° .020	58° .017	60° .014
33	26° .067	27° .065	29° .062	30° .060	31° .058	34° .053	36° .049	38° .045	40° .041	42° .037	44° .034	46° .031	47° .028	50° .024	53° .020	56° .017	58° .014
36	24° .059	25° .057	27° .055	28° .053	29° .052	31° .048	34° .044	36° .041	38° .038	40° .035	42° .032	43° .030	45° .027	48° .023	51° .020	53° .017	55° .014
40	22° .050	23° .049	24° .047	25° .046	27° .045	29° .042	31° .039	33° .037	35° .034	37° .032	39° .030	40° .028	42° .026	45° .022	48° .019	50° .016	52° .014
45	20° .041	21° .040	22° .040	23° .039	29° .038	26° .036	28° .034	30° .032	32° .030	34° .028	35° .027	37° .025	39° .024	42° .021	44° .018	47° .016	49° .014
50	18° .035	19° .034	20° .033	21° .033	22° .032	24° .031	26° .029	27° .028	29° .027	31° .025	33° .024	34° .023	36° .021	39° .019	41° .017	44° .015	46° .013
55	16° .029	17° .029	18° .028	19° .028	20° .027	22° .026	24° .025	25° .024	27° .023	29° .022	30° .021	32° .020	33° .019	36° .018	39° .016	41° .014	43° .013
60	15° .025	16° .025	17° .024	18° .024	18° .024	20° .023	22° .022	23° .021	25° .021	27° .020	28° .019	30° .018	31° .018	34° .016	38° .015	41° .013	43° .012
70	13° .019	14° .019	14° .019	15° .018	16° .018	17° .018	19° .017	20° .017	22° .016	23° .016	24° .015	26° .015	27° .014	30° .013	32° .012	34° .012	37° .011
100,000 CANDLEPOWER SOURCE																	
80	11° 14.748	12° 14.623	13° 14.491	13° 14.412	14° 14.269	15° 14.031	17° 13.708	18° 13.441	19° 13.161	21° 12.789	22° 12.489	23° 12.182	24° 11.870	27° 11.138	29° 10.492	31° 9.848	33° 9.212
100	9° 9.630	10° 9.571	10° 9.539	11° 9.474	11° 9.439	12° 9.330	14° 9.175	15° 9.048	16° 8.914	16° 8.819	18° 8.627	19° 8.475	20° 8.319	22° 7.993	24° 7.654	26° 7.305	27° 7.014
125	7° 6.250	8° 6.223	8° 6.209	9° 6.178	9° 6.163	10° 6.113	11° 6.059	12° 6.001	13° 5.938	14° 5.872	14° 5.828	15° 5.756	16° 5.681	18° 5.521	19° 5.384	21° 5.207	23° 5.022
150	6° 4.370	6° 4.364	7° 4.349	7° 4.342	8° 4.324	8° 4.309	9° 4.280	10° 4.249	11° 4.216	11° 4.195	12° 4.158	13° 4.119	14° 4.078	15° 4.008	16° 3.934	18° 3.834	19° 3.751
175	5° 13′ 3.225	5° 33′ 3.220	6° 3.213	6° 3.210	7° 3.199	7° 3.191	8° 3.174	8° 3.164	9° 3.145	10° 3.124	10° 3.112	11° 3.089	12° 3.064	13° 3.024	14° 2.980	15° 2.933	17° 2.869
200	4° 34′ 2.476	4° 52′ 2.473	5° 9′ 2.470	5° 26′ 2.468	5° 43′ 2.463	6° 2.457	7° 2.446	7° 2.440	8° 2.428	9° 2.415	9° 2.408	10° 2.393	10° 2.385	11° 2.360	12° 2.332	14° 2.294	15° 2.262

TABLE No. 10B

Upper Figures — Angle Between Light Ray and Vertical
Lower Figures — Footcandles on a VERTICAL Plane Produced by a Source of 100 Candlepower

H—HORIZONTAL DISTANCE FROM UNIT—FEET

V = VERTICAL HEIGHT OF LIGHT SOURCE ABOVE SURFACE LIGHTED—FEET	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
4	0° 0′ 0	14° 1.427	27° 2.236	37° 2.400	45° 2.210	51° 1.905	56° 1.599	60° 1.337	63° 1.118	66° .943	68° .800	70° .685	72° .594	73° .517	74° .455	75° .401
5	0° 0′ 0	11° .754	22° 1.281	31° 1.513	39° 1.523	45° 1.414	50° 1.260	54° 1.099	58° .952	61° .824	63° .716	66° .623	67° .547	69° .481	70° .426	72° .378
6	0° 0′ 0	9° .445	18° .791	27° .994	34° 1.067	40° 1.050	45° .982	49° .894	53° .800	56° .711	59° .630	61° .559	63° .498	66° .444	67° .397	68° .355
7	0° 0′ 0	8° .283	16° .518	23° .679	30° .763	36° .786	41° .765	45° .722	49° .666	52° .608	55° .550	58° .497	60° .447	62° .405	63° .366	65° .330
8	0° 0′ 0	7° .191	14° .357	21° .481	27° .559	32° .596	37° .600	41° .560	45° .552	48° .515	51° .476	54° .437	56° .400	58° .366	60° .334	62° .306
9	0° 0′ 0	6° .135	13° .255	18° .351	24° .419	29° .458	34° .474	38° .472	42° .458	45° .437	48° .411	51° .384	53° .356	55° .329	57° .305	59° .280
10	0° 0′ 0	5° 43′ .098	11° .189	17° .264	22° .320	27° .358	31° .379	35° .385	39° .381	42° .370	45° .354	48° .336	50° .316	52° .295	54° .274	56° .256
11	0° 0′ 0	5° 12′ .074	10° .143	15° .202	20° .249	24° .283	29° .305	32° .316	36° .318	39° .313	42° .305	45° .292	48° .278	50° .264	52° .248	54° .233
12	0° 0′ 0	4° 46′ .057	9° .111	14° .158	18° .198	23° .228	27° .248	30° .261	34° .267	37° .267	40° .262	43° .255	45° .246	47° .235	49° .223	51° .211
13	0° 0′ 0	4° 24′ .045	9° .088	13° .126	17° .159	21° .185	25° .206	28° .218	32° .225	35° .228	38° .227	40° .223	43° .217	45° .200	47° .201	49° .192
14	0° 0′ 0	4° 5′ .036	8° .071	12° .102	16° .130	20° .152	23° .170	27° .182	30° .191	33° .195	36° .196	38° .195	41° .191	43° .187	45° .180	47° .174
15	0° 0′ 0	3° 49′ .029	8° .058	11° .084	15° .107	18° .127	22° .142	25° .154	28° .163	31° .168	34° .171	36° .171	39° .170	41° .166	43° .162	45° .157
16	0° 0′ 0	3° 35′ .024	7° .048	11° .070	14° .089	17° .106	21° .120	24° .131	27° .140	29° .146	32° .149	35° .151	37° .150	39° .149	41° .146	43° .142
17	0° 0′ 0	3° 22′ .020	7° .040	10° .058	13° .075	16° .090	19° .102	22° .113	25° .120	28° .127	30° .131	33° .133	35° .133	37° .133	39° .131	41° .129
18	0° 0′ 0	3° 11′ .017	6° .034	9° .050	13° .064	16° .077	18° .088	21° .097	24° .105	27° .110	29° .114	31° .117	34° .119	36° .119	38° .118	40° .117
19	0° 0′ 0	3° 1′ .015	6° .029	6° .042	12° .055	15° .066	18° .076	20° .084	23° .091	25° .097	28° .101	30° .104	32° .105	34° .107	36° .107	38° .106
20	0° 0′ 0	2° 51′ .012	5° 43′ .025	9° .036	11° .047	14° .057	17° .066	19° .074	22° .080	24° .086	27° .090	29° .090	31° .095	33° .096	35° .096	37° .096
21	0° 0′ 0	2° 44′ .011	5° 26′ .021	8° .031	11° .041	13° .050	16° .057	18° .065	21° .070	23° .075	25° .080	28° .083	30° .082	32° .086	34° .087	36° .087
22	0° 0′ 0	2° 36′ .009	5° 10′ .019	8° .027	10° .036	13° .044	15° .050	18° .057	20° .062	22° .067	25° .070	27° .074	29° .076	31° .078	33° .079	34° .078
23	0° 0′ 0	2° 29′ .008	4° 58′ .016	7° .024	10° .031	12° .038	15° .045	17° .050	19° .055	21° .060	24° .063	26° .066	28° .069	29° .071	31° .072	33° .072
24	0° 0′ 0	2° 23′ .007	4° 45′ .014	7° .021	10° .028	12° .034	14° .040	16° .045	18° .049	21° .054	23° .057	25° .060	27° .062	28° .064	30° .065	32° .066
25	0° 0′ 0	2° 17′ .006	4° 34′ .013	7° .019	9° .025	11° .030	14° .035	16° .040	18° .044	20° .048	22° .051	24° .054	26° .056	27° .058	29° .059	31° .061
27	0° 0′ 0	2° 7′ .005	4° 14′ .010	6° .015	8° .020	10° .024	12° .028	15° .032	17° .036	18° .039	20° .042	22° .044	24° .047	26° .048	27° .050	29° .051
30	0° 0′ 0	1° 54′ .004	3° 50′ .007	5° 43′ .011	8° .015	9° .018	11° .021	13° .024	15° .027	17° .029	18° .032	20° .034	22° .036	23° .037	25° .039	27° .040
33	0° 0′ 0	1° 44′ .003	3° 28′ .006	5° 12′ .008	7° .011	9° .013	10° .016	12° .018	14° .020	15° .022	17° .024	18° .026	20° .028	22° .029	23° .031	24° .031
36	0° 0′ 0	1° 36′ .002	3° 11′ .004	4° 46′ .006	6° .008	8° .010	9° .012	11° .014	13° .016	14° .018	16° .019	17° .020	18° .022	20° .023	21° .024	23° .025
40	0° 0′ 0	1° 26′ .002	2° 52′ .003	4° 17′ .005	5° 43′ .006	7° .008	9° .009	10° .010	11° .012	13° .013	14° .014	15° .015	17° .016	18° .018	19° .019	21° .019
45	0° 0′ 0	1° 16′ .001	2° 33′ .002	3° 49′ .003	5° 5′ .004	6° .005	8° .006	9° .007	10° .008	11° .009	13° .010	14° .011	15° .012	16° .013	17° .013	18° .014
50	0° 0′ 0	1° 9′ .001	2° 17′ .002	3° 26′ .002	4° 34′ .003	5° 43′ .004	7° .005	8° .005	9° .006	10° .007	11° .008	12° .008	14° .009	15° .009	16° .010	16° .010
55	0° 0′ 0	1° 2′ .001	2° 5′ .001	3° 7′ .002	4° 10′ .002	5° 9′ .003	6° .003	7° .004	8° .005	9° .005	10° .006	11° .006	12° .007	13° .007	14° .008	15° .008
60	0° 0′ 0	0° 57′	1° 55′ .001	2° 52′ .001	3° 50′ .002	4° 46′ .002	5° 43′ .003	7° .003	8° .004	9° .004	9° .004	10° .005	11° .005	12° .006	13° .006	14° .006
70	0° 0′ 0	0° 49′	1° 38′	2° 34′ .001	3° 16′ .001	4° 5′ .001	4° 54′ .002	5° 43′ .002	7° .002	7° .003	8° .003	9° .003	10° .003.	11° .004	11° .004	12° .004
100,000 CANDLEPOWER SOURCE																
80	0° 0′ 0	0° 43′ .195	1° 26′ .390	2° 9′ .585	2° 52′ .778	3° 35′ .971	4° 17′ .116	5° 0′ 1.35	5° 43′ 1.54	6° 1.73	7° 1.91	8° 2.09	9° 2.26	9° 2.44	10° 2.61	11° 2.78
100	0° 0′ 0	0° 34′ .100	1° 9′ .200	1° 43′ .300	2° 17′ .399	2° 52′ .498	3° 26′ .597	4° 0′ .695	4° 34′ .792	5° 9′ .889	5° 43′ .985	6° 1.08	7° 1.17	7° 1.27	8° 1.36	9° 1.45
125	0° 0′ 0	0° 28′ .051	0° 55′ .102	1° 22′ .153	1° 50′ .204	2° 17′ .255	2° 45′ .306	3° 12′ .357	3° 40′ .407	4° 7′ .457	4° 34′ .507	5° 2′ .557	5° 29′ .606	6° .655	6° .704	7° .751
150	0° 0′ 0	0° 23′ .030	0° 46′ .059	1° 9′ .089	1° 32′ .118	1°55′ .148	2° 17′ .177	2° 40′ .207	3° 2′ .236	3° 26′ .265	3° 49′ .294	4° 11′ .323	4° 34′ .352	4° 57′ .381	5°20′ .409	5° 43′ .438
175	0° 0′ 0	0° 20′ .019	0° 39′ .037	0° 59′ .056	1° 19′ .075	1° 38′ .093	1° 58′ .112	2° 17′ .130	2° 37′ .149	2° 57′ .167	3° 16′ .186	3° 36′ .204	3° 55′ .222	4° 15′ .241	4° 34′ .259	4° 54′ .277
200	0° 0′ 0	0° 17′ .012	0° 34′ .025	0° 52′ .037	1° 9′ .050	1° 26′ .062	1° 43′ .075	2° 0′ .087	2° 17′ .100	2° 35′ .112	2° 52′ .124	3° 9′ .137	3° 26′ .149	3° 43′ .161	4° 0′ .174	4° 17′ .186

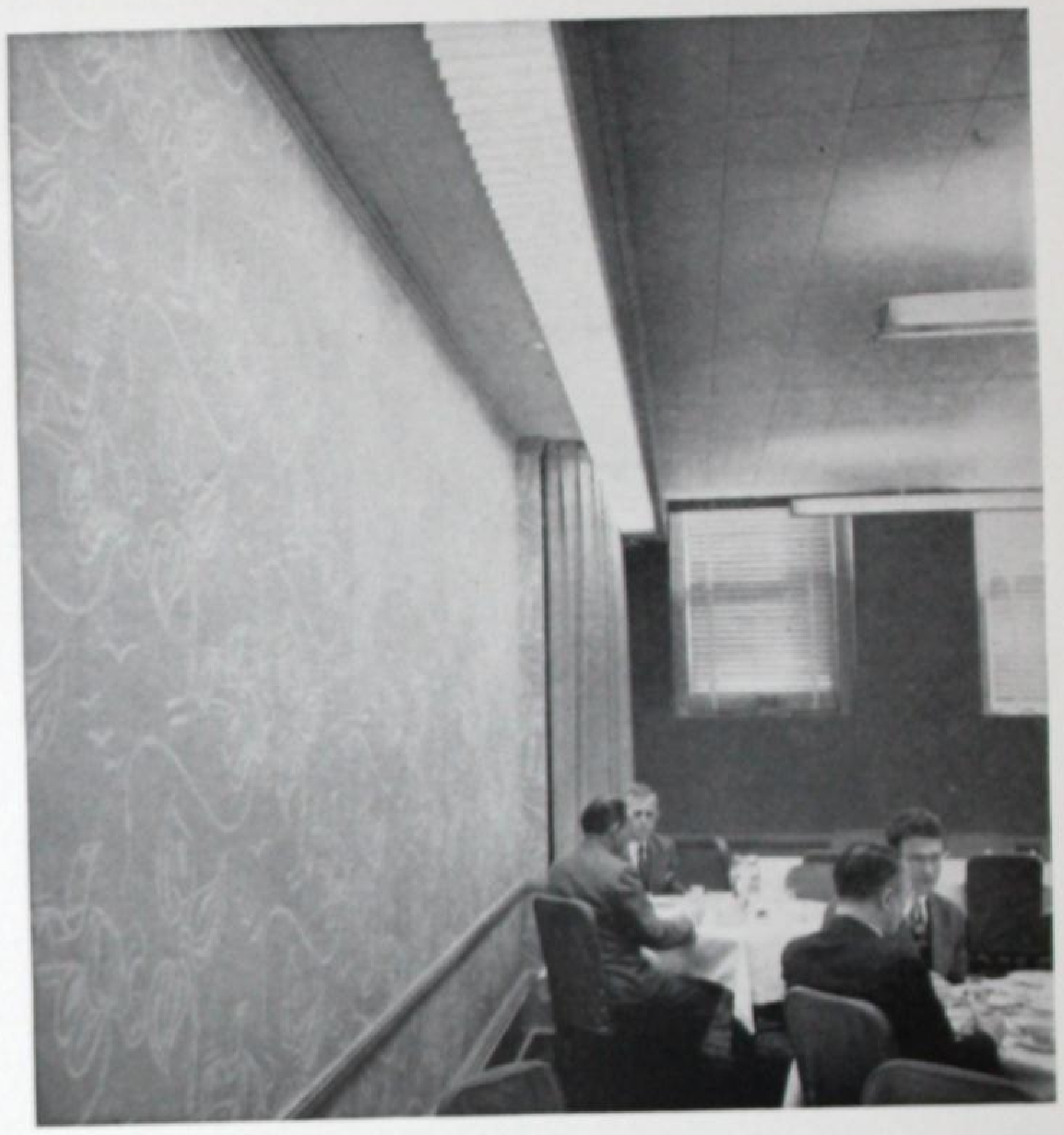
TABLE No. 10B

Upper Figures — Angle Between Light Ray and Vertical
Lower Figures — Footcandles on a VERTICAL Plane Produced by a Source of 100 Candlepower

V = VERTICAL HEIGHT OF LIGHT SOURCE ABOVE SURFACE LIGHTED — FEET	H—HORIZONTAL DISTANCE FROM UNIT—FEET																
	16	17	18	19	20	22	24	26	28	30	32	34	36	40	44	48	52
4	76° .360	77° .319	78° .288	78° .261	79° .235	80° .204	81° .168	81° .143	82° .126	82° .112	83° .096	83° .085	84° .072	84° .060	85° .055	85° .048	86° .039
5	73° .339	74° .306	74° .277	75° .251	76° .228	77° .194	78° .163	79° .140	80° .123	81° .102	81° .096	82° .082	82° .072	83° .064	84° .053	84° .048	85° .042
6	69° .320	71° .289	71° .264	72° .241	73° .220	75° .187	76° .160	77° .139	78° .121	79° .105	79° .091	80° .085	80° .072	81° .060	82° .051	83° .040	83° .035
7	66° .299	68° .274	69° .249	70° .228	71° .211	72° .179	74° .154	75° .134	76° .116	77° .103	78° .191	78° .083	79° .072	80° .057	81° .050	82° .041	82° .037
8	63° .280	65° .257	66° .236	67° .216	68° .200	79° .173	72° .150	73° .130	74° .112	75° .098	76° .088	77° .081	77° .072	79° .060	80° .050	81° .042	81° .039
9	61° .260	62° .238	63° .220	65° .205	66° .189	68° .164	69° .141	71° .124	72° .109	73° .097	74° .089	75° .079	76° .072	77° .058	78° .049	79°. .043	80° .035
10	58° .238	60° .221	61° .207	62° .192	63° .178	66° .156	67° .137	69° .120	70° .106	72° .096	73° .086	74° .075	74° .068	76° .056	77° .048	78° .043	79° .036
11	56° .218	57° .204	59° .191	60° .180	61° .167	63° .148	65° .131	67° .116	69° .102	70° .093	71° .081	72° .074	73° .069	75° .055	76° .048	77° .039	78° .033
12	53° .200	55° .188	56° .178	58° .168	59° .158	61° .139	63° .124	65° .110	67° .100	68° .090	69° .080	71° .074	72° .066	73° .057	75° .048	76° .040	77° .035
13	51° .182	53° .174	54° .165	56° .155	57° .148	59° .132	62° .118	63° .106	65° .095	67° .085	68° .079	69° .071	70° .064	72° .052	74° .044	75° .044	76° .032
14	49° .167	51° .159	52° .152	54° .145	55° .137	58° .124	60° .111	62° .100	63° .092	65° .084	66° .075	68° .068	69° .062	71° .051	72° .044	74° .038	75° .033
15	47° .151	49° .146	50° .140	52° .134	53° .128	56° .116	58° .106	60° .095	62° .088	63° .080	65° .073	66° .066	67° .060	69° .051	71° .044	73° .038	74° .031
16	45° .138	47° .134	48° .129	50° .125	51° .119	54° .110	56° .100	58° .091	60° .084	62° .077	63° .070	65° .064	66° .058	68° .050	70° .044	72° .036	73° .032
17	43° .126	45° .122	47° .119	48° .115	50° .111	52° .102	55° .097	57° .087	59° .079	60° .074	62° .068	63° .062	65° .057	67° .049	69° .041	71° .037	72° .031
18	42° .115	43° .112	45° .109	47° .106	48° .102	51° .097	53° .089	55° .082	57° .076	59° .070	61° .064	62° .060	63° .056	66° .047	68° .042	69° .035	71° .032
19	40° .104	42° .103	43° .100	45° .098	46° .095	49° .089	52° .083	54° .078	56° .072	58° .066	59° .062	61° .057	62° .053	65° .046	67° .039	68° .035	70° .030
20	39° .095	40° .094	42° .093	44° .090	45° .088	48° .084	50° .079	52° .074	54° .069	56° .064	58° .059	60° .056	61° .052	63° .044	66° .040	67° .034	69° .031
21	37° .087	39° .087	41° .085	42° .083	44° .082	46° .079	49 .074	51° .069	53° .065	55° .061	57° .058	58° .053	60° .050	62° .044	64° .038	66° .034	68° .030
22	36° .079	38° .079	39° .079	41° .079	42° .076	45° .073	47° .070	50° .066	52° .062	54° .059	55° .055	57° .051	59° .047	61° .042	63° .038	65° .033	67° .028
23	35° .073	36° .072	38° .072	40° .072	41° .070	44° .068	46° .066	49° .062	51° .060	53° .056	54° .053	56° .049	57° .047	60° .040	62° .036	64° .031	66° .029
24	34° .067	35° .067	37° .067	38° .066	40° .066	43° .064	45° .061	47° .058	49° .056	51° .052	53° .049	55° .047	56° .045	59° .040	61° .035	63° .032	65° .028
25	33° .061	34° .062	36° .062	37° .062	39° .061	41° .060	44° .058	46° .055	48° .053	50° .050	52° .047	54 .045	55 .043	58 .038	60° .033	62° .031	64° .027
27	31° .052	32° .052	34° .053	35° .053	37° .053	39° .052	42° .051	44° .049	46° .048	48° .046	50° .044	52° .042	53° .040	56° .036	58° .033	61° .028	63° .025
30	28° .041	30° .041	31° .042	32° .042	34° .043	36° .043	39° .042	41° .042	43° .040	45° .039	47° .038	49° .036	50° .035	53° .032	6° .029	58° .027	60° .024
33	26° .032	27° .033	29° .034	30° .035	31° .035	34° .035	36° .036	38° .035	40° .035	42° .034	44° .033	46° .032	47° .031	50° .029	53° .027	56° .025	58° .022
36	24° .026	25° .027	27° .028	28° .028	29° .029	31° .029	34° .029	36° .030	38° .030	40° .029	42° .028	43° .028	45° .027	48° .026	51° .024	53° .023	55° .020
40	22° .020	23° .021	24° .021	25° .022	27° .022	29° .023	31° .023	33° .024	35 .024	37 .024	39 .024	40° .024	42° .023	45° .022	48° .021	50° .019	52° .018
45	20° .015	21° .015	22° .016	23° .016	29° .017	26° .018	28° .018	30° .018	32° .019	34° .019	35° .019	37° .019	39° .019	42° .019	44° .018	47° .017	49° .016
50	18° .011	19° .012	20° .012	21° .013	22° .013	24° .014	26° .014	27° .015	29° .015	31° .015	33° .015	34° .016	36° .015	39° .015	41° .015	44° .014	46° .014
55	16° .008	17° .009	18° .009	19° .010	20° .010	22° .010	24° .011	25° .011	27° .012	29° .012	30° .012	32° .012	33° .012	36° .013	39° .013	41° .012	43° .012
60	15° .007	16° .007	17° .007	18° .008	18° .008	20° .008	22° .010	23° .009	25° .010	27° .010	28° .010	30° .010	31° .011	34° .011	38° .011	41° .010	43° .010
70	13° .004	14° .005	14° .005	15° .005	16° .005	17° .006	19° .006	20° .006	22° .006	23° .007	24° .007	26° .007	27° .007	30° .007	32° .008	34° .008	37° .008
	100,000 CANDLEPOWER SOURCE																
80	11° 2.95	12° 3.11	13° 3.26	13° 3.42	14° 3.57	15° 3.86	17° 4.11	18° 4.37	19° 4.61	21° 4.80	22° 5.00	23° 5.18	24° 5.34	27° 5.57	29° 5.77	31° 5.91	33° 5.99
100	9° 1.54	10° 1.63	10° 1.72	11° 1.80	11° 1.89	12° 2.05	14° 2.20	15° 2.35	16° 2.50	16° 2.65	18° 2.76	19° 2.88	20° 2.99	22° 3.20	24° 3.37	26° 3.51	27° 3.65
125	7° .800	8° .846	8° .894	9° .939	9° .986	10° 1.08	11° 1.16	12° 1.25	13° 1.33	14° 1.41	14° 1.49	15° 1.57	16° 1.64	18° 1.77	19° 1.90	21° 2.00	23° 2.09
150	6° .466	6° .495	7° .522	7° .550	8° .577	8° .632	9° .685	10° .736	11° .787	11° .839	12° .887	13° .934	14° .979	15° 1.07	16° 1.15	18° 1.23	19° 1.30
175	5° 13′ .295	5° 33′ .313	6° .330	6° .349	7° .366	7° .401	8° .435	8° .470	9° .503	10° .536	10° .569	11° .600	12° .630	13° .691	14° .749	15° .804	17° .852
200	4° 34′ .198	4° 52′ .210	5° 9′ .222	5° 26′ .234	5° 43′ .246	6° .270	7° .294	7° .317	8° .340	9° .362	9° .385	10° .407	10° .429	11° .472	12° .513	14° .551	15° .588

display rack

wall ▶



niche

wall case

The predetermining of lighting levels for supplementary systems may be accomplished by one of several methods previously outlined, such as the point-by-point method (page 73), the beam lumens method (page 81), and by use of tables and curves as presented in various forms in manufacturers' catalogs and data sheets.

The predetermining of lighting levels for supplementary systems in which "continuous" linear sources are used may be accomplished from empirical data based on the Lumens-per-foot of the source. These data are adaptable for relatively short distances between the light source and the work or display where the inverse square law obviously does not apply. The "Lumens-per-foot" method employs the following formulas:

Where the lamp and reflector have been selected—

Footcandles = K x Lumens-per-foot of Source.

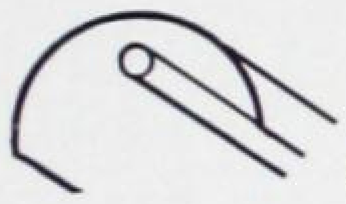
Where a footcandle level is desired—

$$\text{Necessary Lumens-per-foot} = \frac{\text{Fc Desired}}{\text{K}}$$

in which the constants K_H and K_V apply respectively to Horizontal and Vertical illumination values, as given in the charts below:

TABLE A—HORIZONTAL ILLUMINATION

Horizontal Fc = (K_H × Lamp — Lumens-per-foot
Broad Distribution—White Enamel Reflector



K_H Values — DISTANCE FROM CENTER LINE OF UNIT

Distance Between Lamp Center and Plane of Measurement		1′	2′	3′
1 Ft.	.438	.127	.008	.001
2 Ft.	.223	.150	.061	.017
3 Ft.	.145	.120	.077	.041
4 Ft.	.106	.095	.072	.048

TABLE B—HORIZONTAL ILLUMINATION

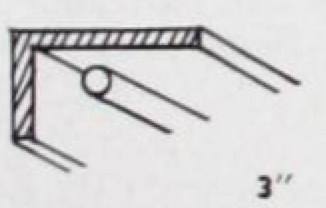
Horizontal Fc = (K_H × Lamp — Lumens-per-foot
Narrow Distribution—Polished Aluminum Reflector

K_H Values — DISTANCE FROM CENTER LINE OF UNIT

Distance Between Lamp Center and Plane of Measurement		1′	2′	3′
1 Ft.	.753	.079	. . .	. . .
2 Ft.	.330	.165	.035	.006
3 Ft.	.212	.161	.066	.022
4 Ft.	.153	.131	.086	.038

TABLE C—VERTICAL ILLUMINATION

Vertical Fc = (K_V × Lamp — Lumens-per-foot)
Broad Distribution—White Painted Cornice, No Reflector

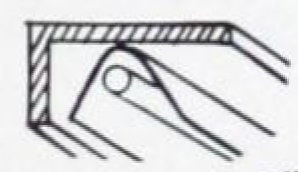


K_V Values — DISTANCE FROM CENTER LINE OF UNIT

Distance Between Lamp Center and Plane of Measurement	3″	6″	9″	12″	18″
1 Ft.	.185	.159	.175	.165	.129
2 Ft.	.011	.028	.044	.057	.068
3 Ft.	.004	.010	.017	.023	.032
4 Ft.	.002	.005	.008	.012	.018

TABLE D—VERTICAL ILLUMINATION

Vertical Fc = (K_V × Lamp — Lumens-per-foot)
Narrow Distribution—Polished Aluminum Reflector



K_V Values — DISTANCE FROM CENTER LINE OF UNIT

Distance Between Lamp Center and Plane of Measurement	3″	6″	9″	12″	18″
1 Ft.	.121	.125	.135	.096	.080
2 Ft.	.028	.056	.077	.086	.090
3 Ft.	.010	.028	.036	.044	.059
4 Ft.	.006	.013	.020	.031	.037

Two types of luminaires are specified—Broad distribution as from a unit with a mat-finish reflector and Narrow distribution as from a polished metal reflector. The beam in both cases is presumed to be aimed at a plane 4 feet from the source through point A.

The importance of the reflector is evident from a comparison of Tables C and D. The average K value at 4 feet in C is .009; in D, .021. This difference is 133 per cent.

The actual values from which the tables were compiled are readings taken at the mid-point of luminaires 12 feet in length. For conventional lighting systems, the footcandle levels would normally drop at the ends of rows, unless additional lamps or lamps of higher output are provided.

The values are given for horizontal footcandles at levels of 1, 2, 3, and 4 feet. For example, it is desired to determine the horizontal footcandle level on a work bench 3 feet below a continuous reflector of broad distribution containing *double* rows of 40-watt T-12 standard cool white F lamps. The K_H factor at 3 feet is .145 (average over a 6-inch zone). The lumens-per-foot (Table 11), is 625. Multiplying this by 2 (rows) and by .145 equals 181 footcandles (initial).

A vertical illumination value of 50 footcandles is desired on a display lighted by a narrow beam reflector unit 1 foot up and 9 inches out. The formula to apply is:

$$\text{Necessary Lumens/ft.} = \frac{\text{Ft-c}}{K_V}$$

The K_V value as seen in Table D is .135; hence $\frac{50}{.135}$ = 370. From Table 11, a suitable lamp is selected. In most installations it is wise to supply ¼ to ⅓ additional lumens initially to allow for the normal depreciation of lamps and reflecting surfaces.

TABLE 11 — Lumens-per-foot (Initial Lumens-per-Nominal-Length) — Fluorescent Lamps (Standard Cool White)**

Lamp Desig. GENERAL LINE	Lumens per. ft.	Lumens (Init.)	Nominal Length	Lamp Desig. SLIMLINE	Lumens per ft.	Lumens (Init.)	Nominal Length	Watts
4 w T-5	200	100	6″	42″ T-6	423	1480	42″	25.0
6 w T-5	280	210	9″	64″ T-6	440	2350	64″	37.0
8 w T-5	320	320	12″	72″ T-8	425	2550	72″	36.5
13 w T-5	390	680	21″	96″ T-8	437	3550	96″	49.0
14 w T-12	430	540	15″	48″ T-12	575	2300	48″	38.0
15 w T-8	487	730	18″	72″ T-12	600	3600	72″	55.0
15 w T-12	410	615	18″	96″ T-12	631	5050	96″	74.0
20 w T-12	500	1000	24″					
25 w T-12	545	1550	33″	**RAPID START**				
30 w T-8	613	1840	36″	48″ T-12	625	2500	48″	40.0
40 w T-12	625	2500	48″	72″ T-12	883	5300	72″	85.0
40 w T-17	600	2400	60″	96″ T-17	850	6800	96″	100.0
90 w T-17	1030	5150	60″					
100 w T-17	970	4850	60″					

** For lumens-per-foot of other colors, use these multiplying factors: (Std. Cool White = 1.0): DeLuxe Cool White, .71; DeLuxe Warm White. .71; Daylight, .93; Soft White, .68; Green, 1.2; Gold, .6; Blue, .45; Pink, .45; Red, .06.

FLOODLIGHTING

Beam-Lumens Method

In many locations in which floodlighting is proposed, there are some basic dimensions that can be assumed to be already fixed. For example, in the usual ground-area floodlighting, the designer is usually able to locate points where the equipment should logically be placed, such as on nearby buildings, along high banks or fences, or on poles or towers. These locations establish the approximate distance (D) from the floodlight to the surface to be lighted (Fig. 106) and the average aiming angles (Figs. 108a, b, c). They also guide the choice of floodlight type—narrow, medium, or broad-beam as listed in Table 14.

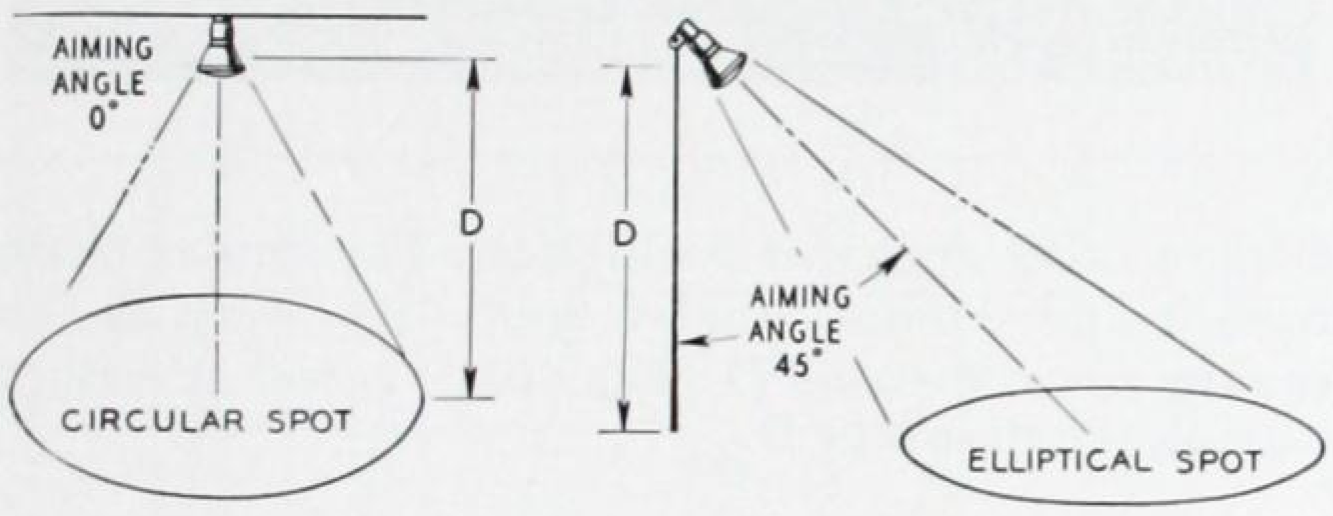


Fig. 106 D is the shortest distance from the floodlight to the plane of the surface to be lighted. The beam is circular when the Aiming Angle is 0°; it is elliptical at other angles.

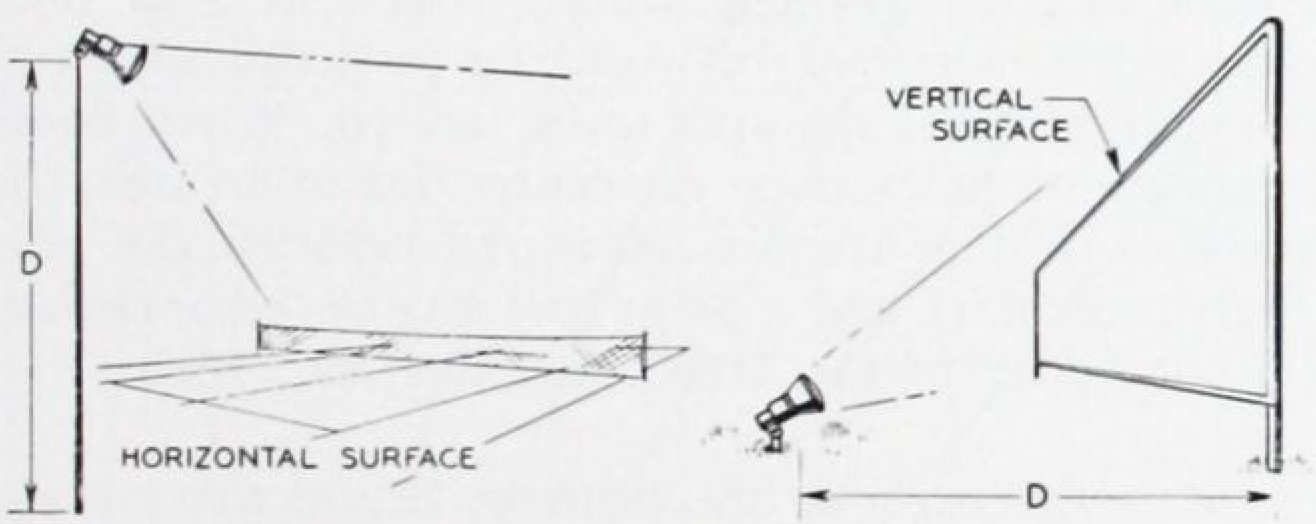


Fig. 107 The distance D applies to lighting horizontal surfaces and vertical surfaces as shown.

As a general rule, it is wiser to design a system with a small number of large filament lamp floodlights rather than a large number of small ones. This makes a simpler system to install, to control, and to maintain. Another reason is that in general the larger the lamp the more efficient it is.

The 1500-watt floodlight in Table 15 sets a practical upper limit to size. It should be remembered, however, that large floodlights are hard to conceal; this is important where their daytime appearance may be objectionable architecturally.

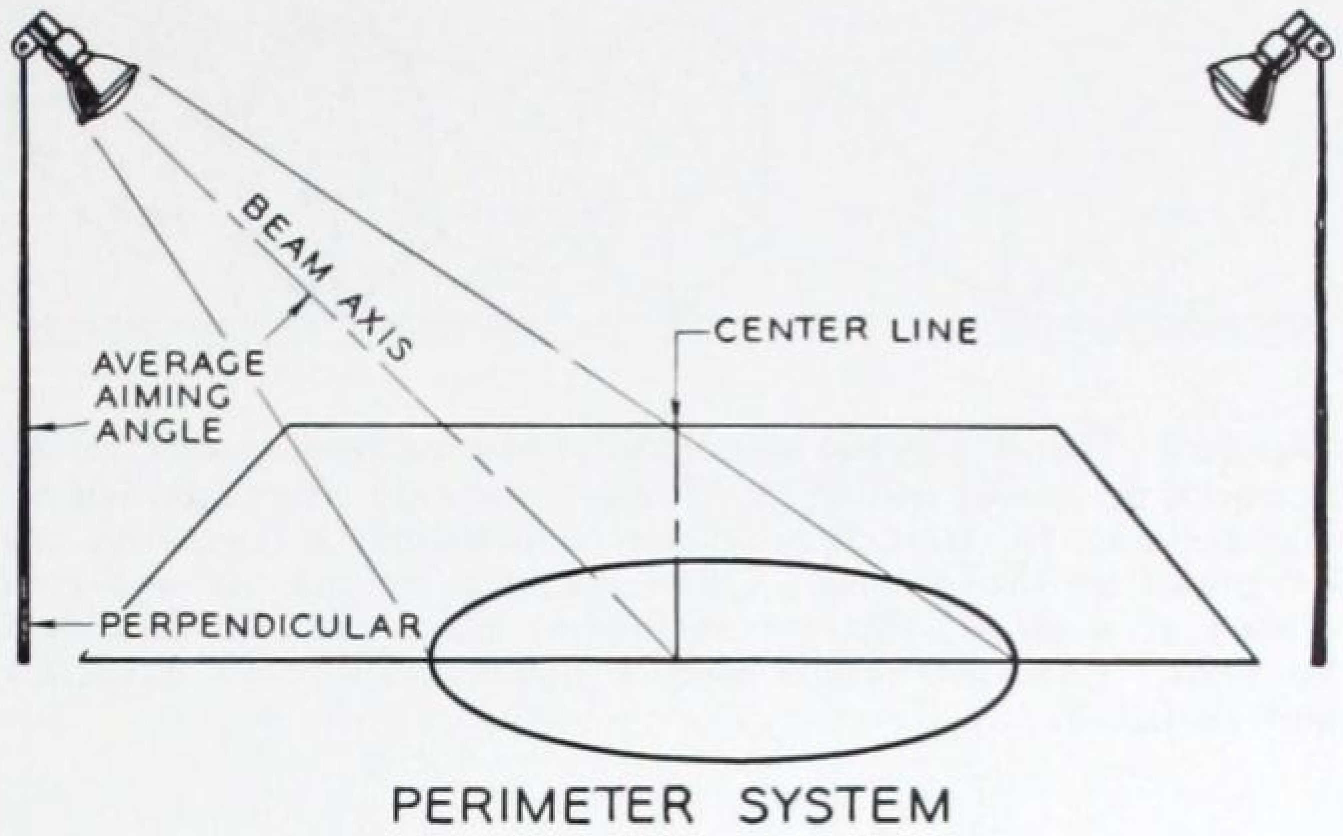


Fig. 108 a—The average Aiming Angle is the angle between the perpendicular and the axis of a floodlight aimed toward the center-line of the surface to be lighted. Illustration shows "perimeter" system.

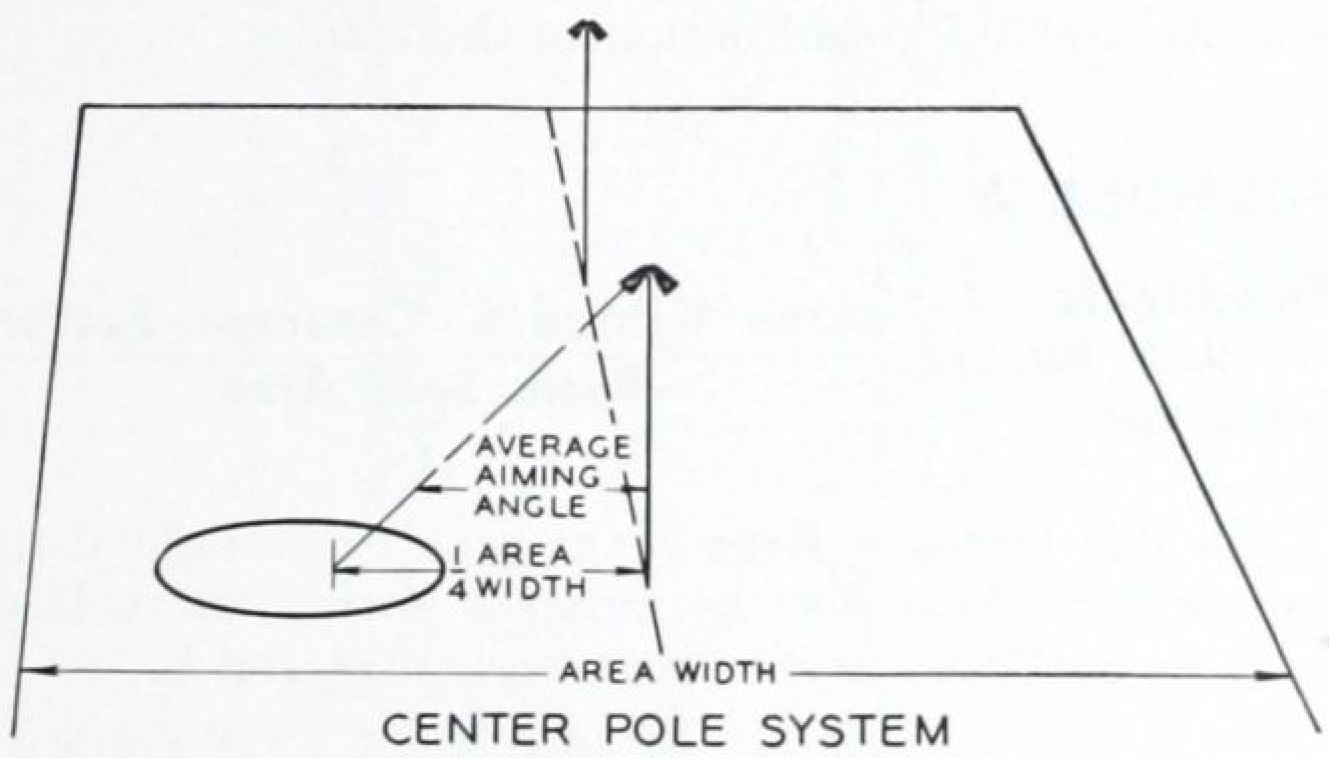


Fig. 108 b—The average Aiming Angle in this "center-pole" system is measured between the perpendicular and a point half way to the perimeter ($\frac{1}{4}$ the total area width).

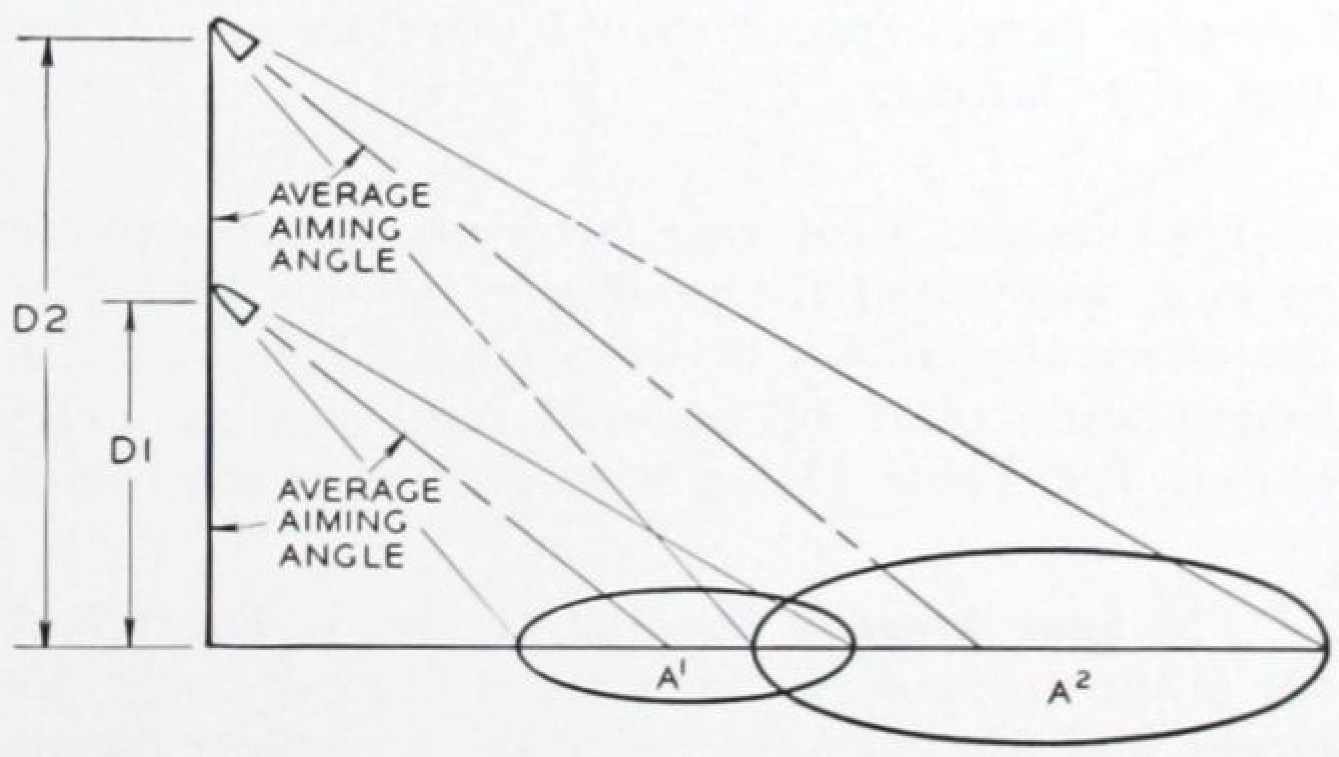


Fig. 108 c—For the same Beam Spread and Aiming Angle, Spot Areas vary as the **square** of the distance D. Spot Length (L) and Spot Width (W) vary **as** the distance D. The Spot Area may be determined by the formula: $L \times W \times \frac{\pi}{4}$

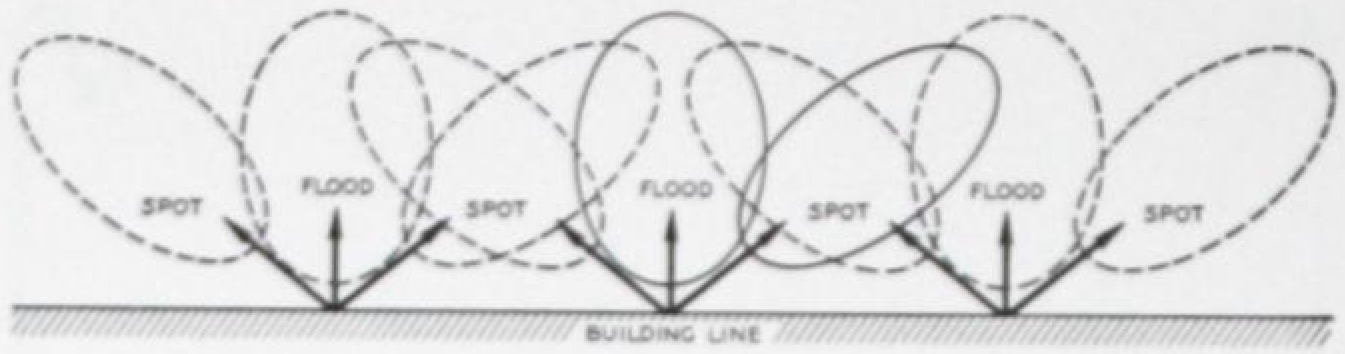


Fig. 109 Floodlights are generally fanned out from towers, poles, or points on nearby buildings. Aiming plans are often supplied by manufacturers for large installations; with them the luminaires can be preset on the ground. Other methods include trial-and-error aiming at night. Sights are sometimes built into the floodlight housings. Checking results with a lightmeter is both necessary and desirable.

All floodlighting design methods include certain approximations, based on experience. In floodlighting systems containing a large number of luminaires, a detailed study of aiming diagrams and many calculations are usually required.* A method, useful for designing simpler systems, called the "beam-lumens" method, requires the solution of two formulas (A and B) and the coordination of the results.

FORMULA A

$$\text{Floodlights Needed for Coverage} = \frac{\text{Area lighted} \times \text{Coverage Factor}}{\text{Beam Spot Area}}$$

In this formula, **Area** is the area to be lighted in square feet. This may be either a horizontal surface or a vertical one, as shown in Figs. 107a and b.

The **Coverage Factor** indicates the minimum number of directions from which each point in the area should be lighted, depending upon the use of the area. A coverage factor of 1 is acceptable in some applications, although in such systems one or two lamp burnouts might temporarily leave large, dark patches. Coverage factors greater than 1 therefore add desireable safety factors.

For example, a coverage factor of 2 is necessary for parking spaces and for protective lighting to reduce the effect of shadows between automobiles, rows of freight cars, piles of material, and similar bulky objects. See Table 13 for other recommended values.

The **Spot Areas** of floodlight beams in Formula A are given in Table 12 for various beam spreads, distances, and Aiming Angles of usual equipment having symmetrical candlepower distribution. In this table, D is the perpendicular distance measured from the floodlight to the plane of the lighted surface. L and W are the lengths and widths of the ellipses formed when floodlights are aimed at an angle to the lighted surface. At 0° the area is usually circular (Fig. 106a);

* References: National Electric Manufacturers Association Standards Bulletin FL; IES Lighting Handbook; GE Bulletin LD-10 "Lighting for Sports & Recreation"; and LD-20 "Protective Lighting."

at most other angles, it is elliptical. For similar beam spreads and Aiming Angles, Spot Areas vary as the **square** of the distance D (Fig. 107c). L and W values vary **as** the distances D.

The average Aiming Angle in Table 12 is measured from the perpendicular to the beam axis line (Fig. 108a). In a "perimeter" system in which the floodlights are mounted along or beyond the perimeter of an area, they will, of course, be aimed at various angles, but the **average** Aiming Angle used in computation is measured between the perpendicular and the center-line of the area to be lighted. When floodlights are on poles along the center-line of an area, the average Aiming Angle is measured between the pole (perpendicular) and a point half way to the boundary (¼ the width of the total area). See Fig. 108b.

After determining the distance D and the average Aiming Angle, the Spot Area is found from Table 12 and Formula A can be solved.

The next step is to solve **Formula B** to calculate the number and size of floodlights needed to supply the necessary footcandles.

FORMULA B

$$\text{Floodlights Needed for Footcandles} = \frac{\text{Footcandles} \times \text{Area Lighted}}{\text{Maintenance Factor} \times \text{Utilization Factor} \times \text{Beam Lumens}}$$

For this formula, typical **Footcandle** recommendations are given in Table 13. The **Maintenance Factor** allows for dust and dirt and normal lamp depreciation. This is found under average conditions to be about .7. However, it may be as low as .3 for extremely dirty locations, where dust, dirt, and smoke are frequently suspended in the air.

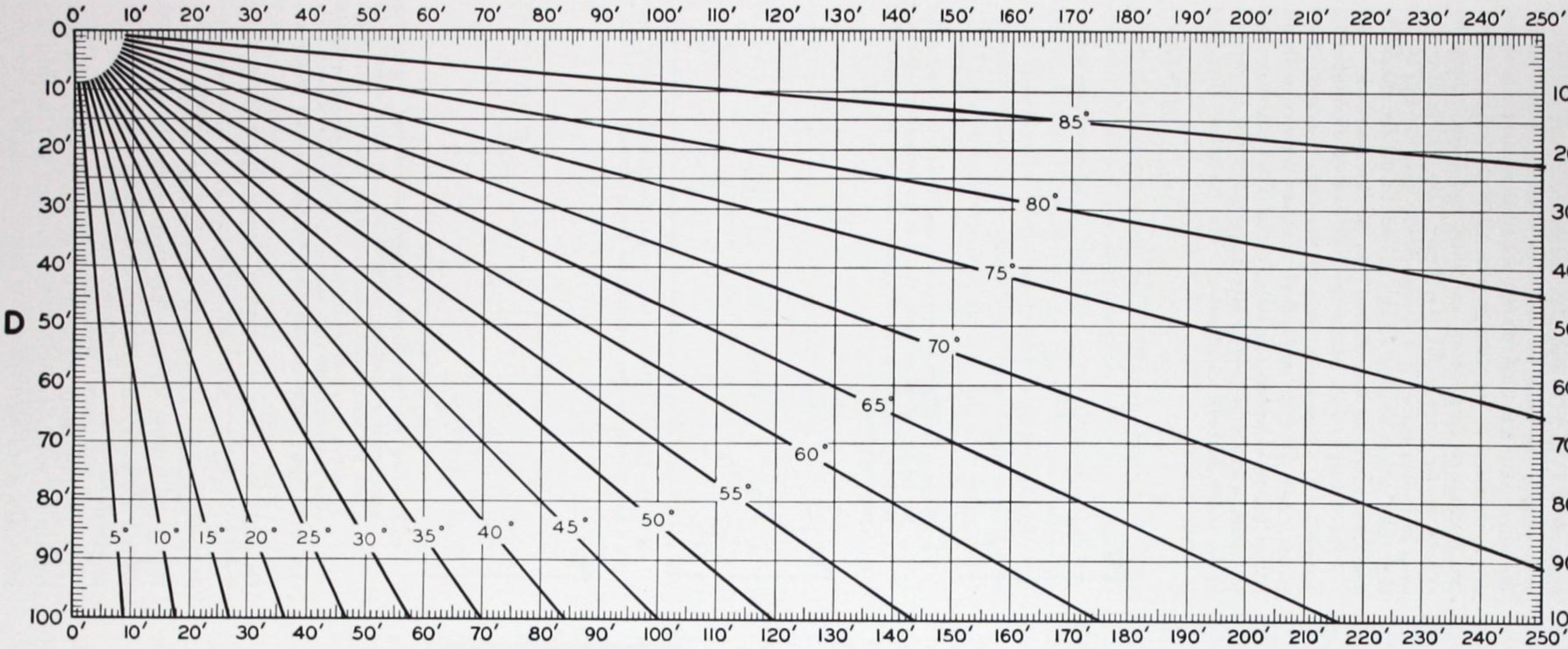


Fig. 110 Chart of Aiming Angles and D Distance

Top and bottom scales are horizontal distances (H) in lighting horizontal surfaces. By turning the chart 90° these become vertical distances in systems for lighting vertical surfaces.

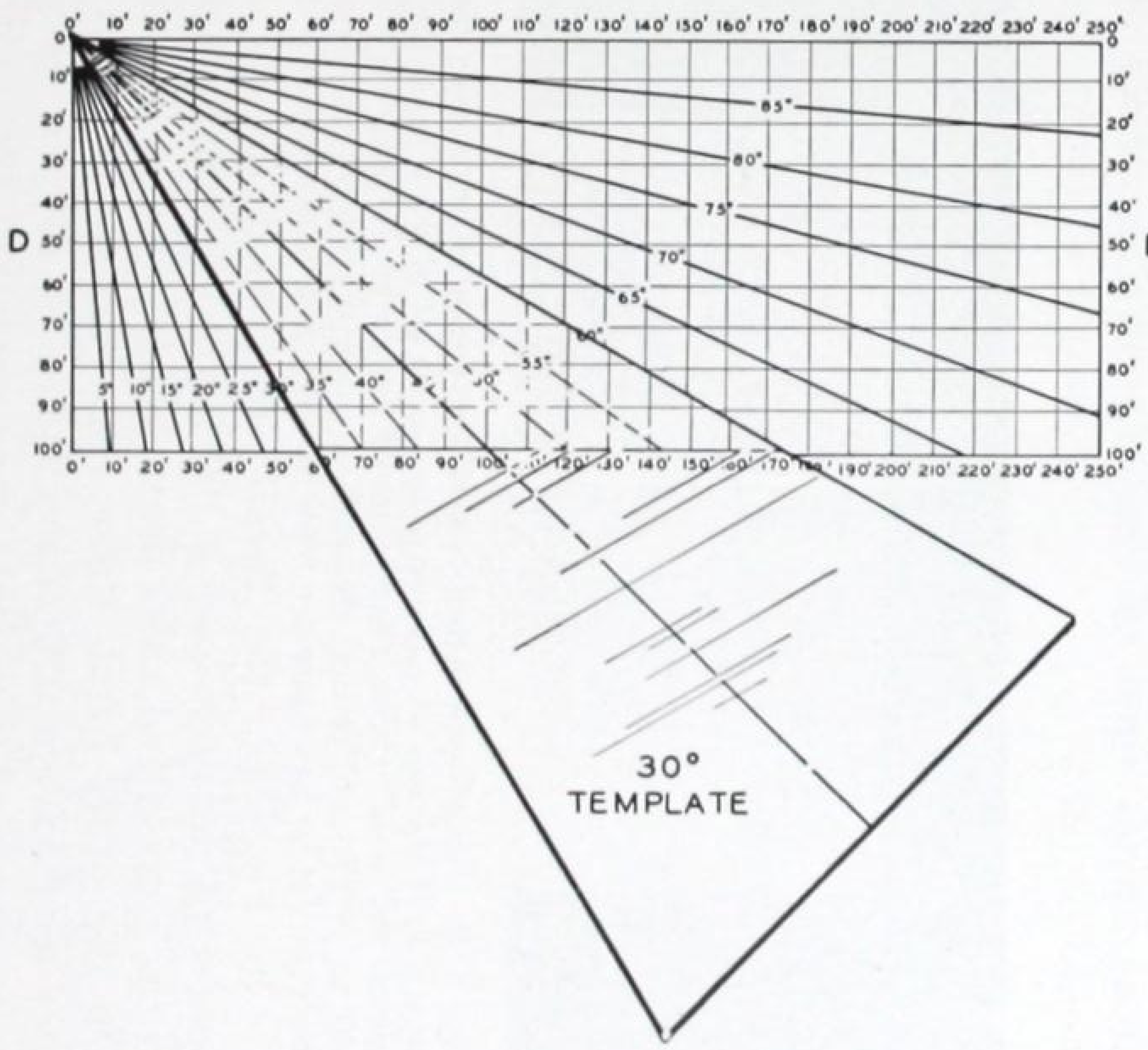


Fig. 110a Templates of 15°, 30°, and 50° help to visualize results and guide the choice of floodlight types. In general, for short throws, wide-beam floodlights and PAR and R-type lamps are used; for long throws, medium or narrow-beam floodlights are selected.

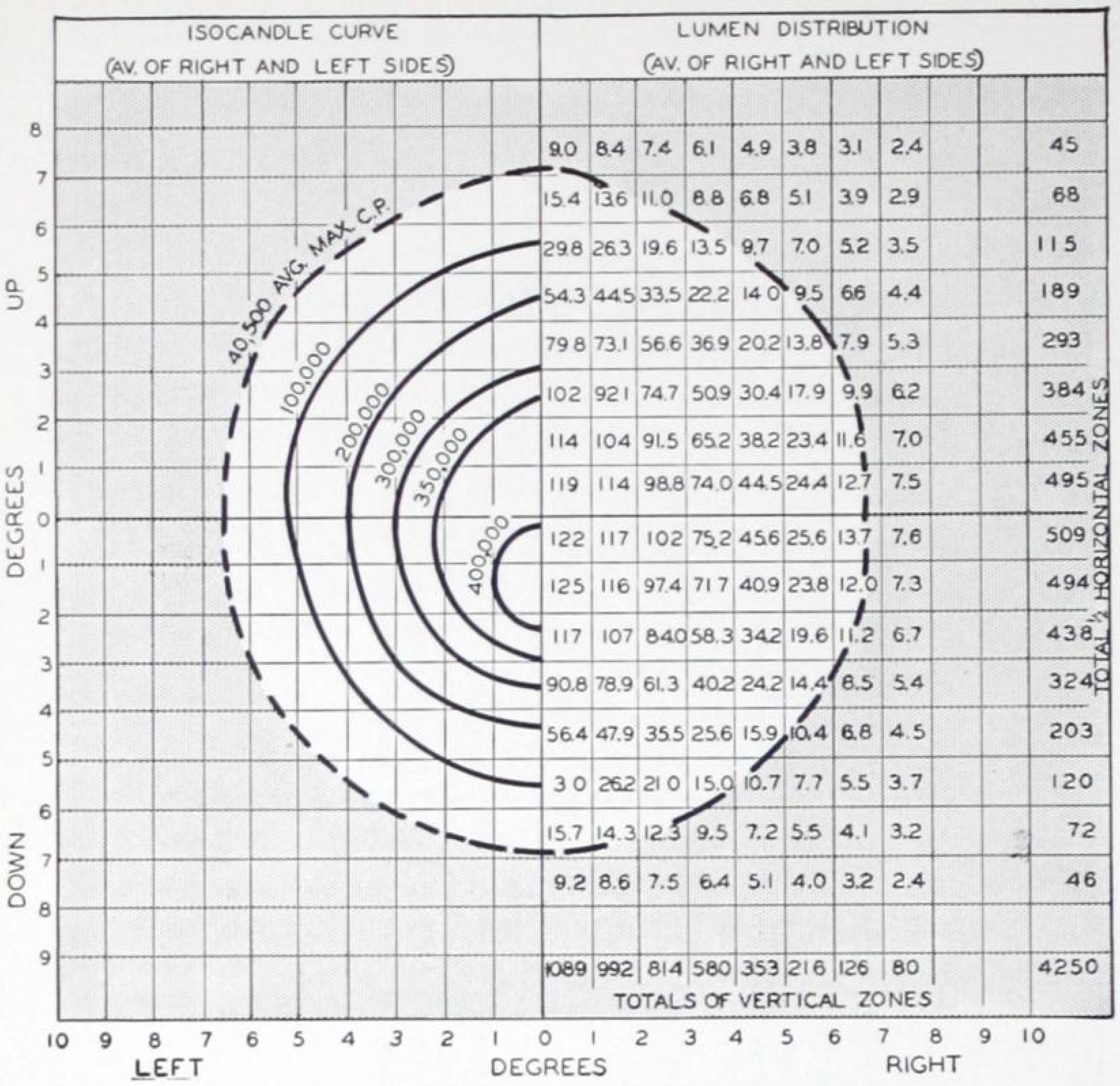


Fig. 111 Floodlight beam pattern tested according to the "I.E.S. Testing Specifications."* Test data are plotted on a series of squares from 1° to 3° in dimension, the choice of size depending upon whether the beam has narrow or wide spread distribution. The testing range is usually 100 feet and at this distance one square degree represents an area 20.94 inches by 20.94 inches. About 100 readings of candlepower are taken, and these include the extreme angular range of the stray light. Tests usually involve a series of stations spaced in a regular manner over the area of the beam, plus stations on eight equally spaced radial lines. Isocandle distribution curves are then plotted from the data obtained.

The lumens in each square (see right half of illustration) are the product of a constant × distance² × average footcandle level in the square. The "beam lumens" constitute the sum of all the lumens of the individual test areas, except those squares or parts of squares in which the candlepower measures less than 10 per cent of the maximum beam candlepower. The "so-called" stray light is shown shaded.

The **Utilization Factor** is the ratio of the lumens effectively lighting an area to the beam lumens, expressed as a decimal fraction. Most floodlights and projector- and reflector-type lamps are rated in **Beam Lumens.** As shown in Fig. 111, the **Beam Lumens** include only the lumens in that part of the beam in which the candlepower values are 10 per cent or more of the maximum candlepower. For typical values, see Table 15 and Footnote**, below. These data may change from time to time so current values only should be used.

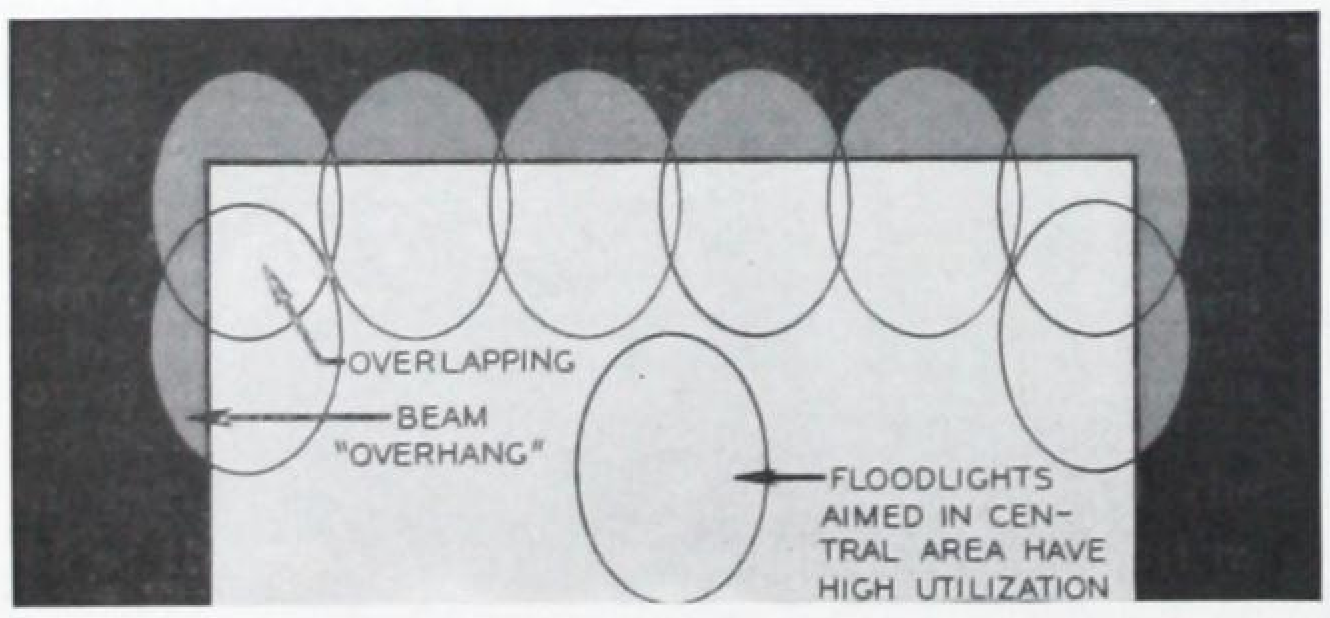
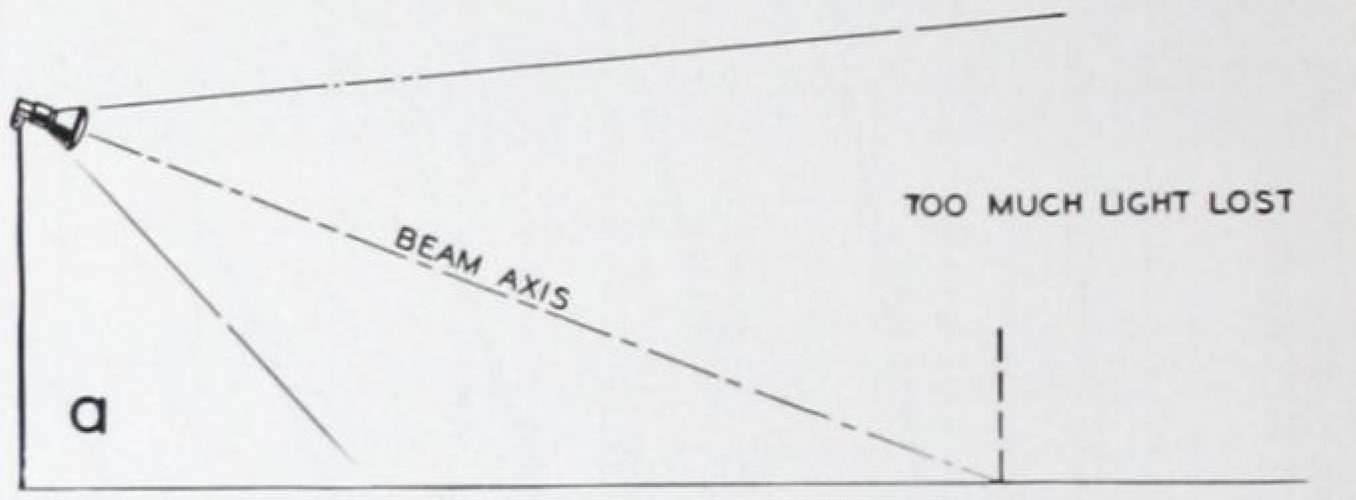


Fig. 112 Floodlights aimed toward the center of an area as shown have 100% (beam-lumen) utilization since all of their beam lumens fall on the area. Those aimed toward the perimeter may vary from .40 to .90 in utilization, depending upon their position. The six spots on the far boundary are from floodlights equally spaced.

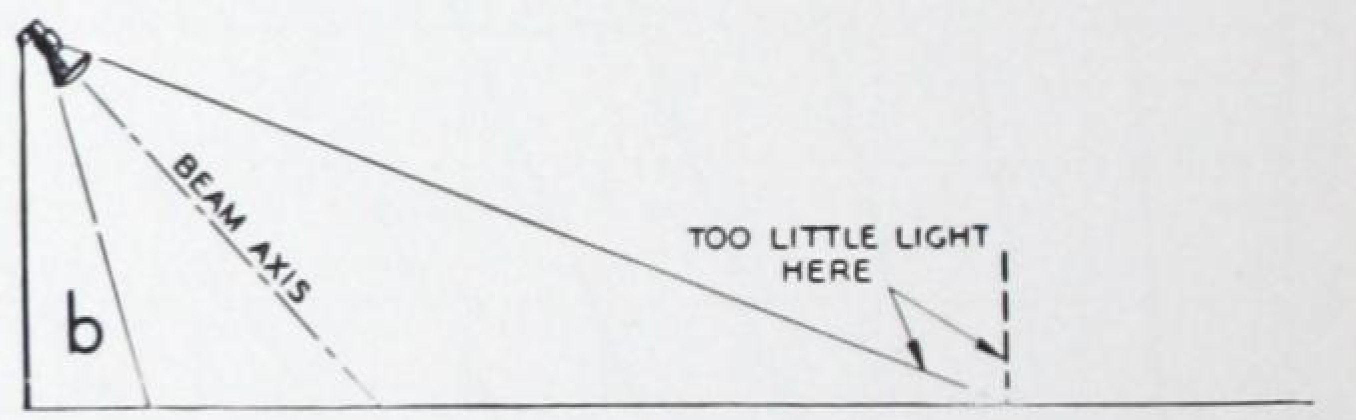
In Fig. 112, the floodlights aimed toward the center of the area have a 100% (beam lumen) utilization, since all of their beam lumens fall on the area. On the other hand, those aimed toward the perimeter may have a utilization factor of 40% or less because much of their light must necessarily fall outside the area.

From this the following conclusions can be drawn:

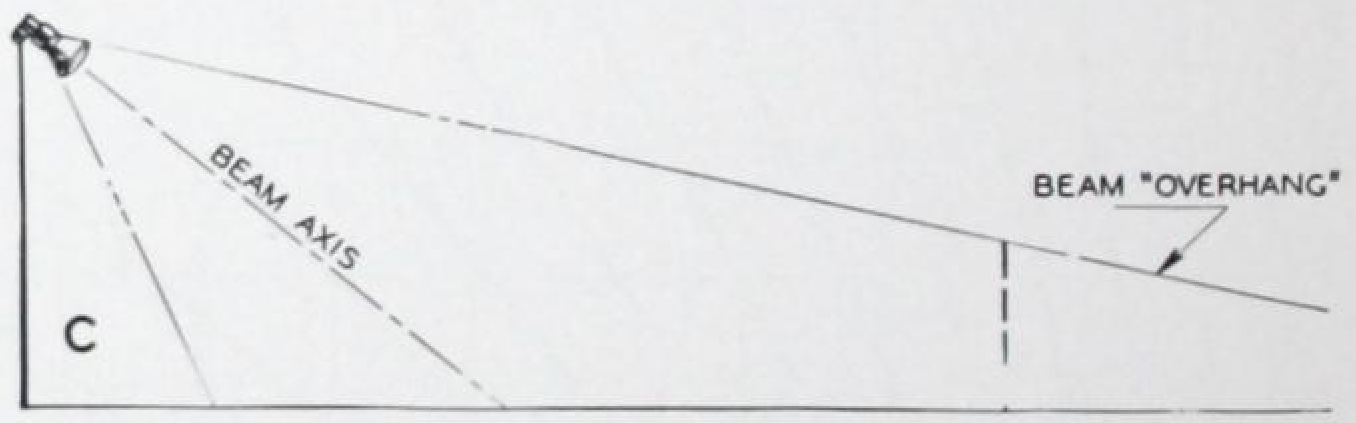
1. If half or more than half of the floodlights are aimed so that all their beam lumens fall within an area, the over-all Utilization Factor will be about .75.



a. When a floodlight is pointed so that its axis is aimed at the far boundary of an area, there is considerable light lost outside. The glare may be very annoying to neighboring premises also.



b. If the top of the beam is aimed at the field boundary, too little light reaches the area at the perimeter.



c. Pointing the floodlight somewhere between these two extremes is a practical compromise. To have about one-fourth the beam overlap the boundary, raise 15° floodlights 5° above position illustrated in b; for 30° floodlights, raise the floodlight 10°; and for 50° floodlights, raise them 20° for similar approximate coverage at the boundary.

Fig. 113 The aiming of "perimeter" floodlights affects the results and the system utilization considerably.

2. If from one-quarter to one-half of the floodlights are aimed so that all their beam lumens fall within an area, the over-all utilization factor will be about .60.

3. If less than one-quarter of the floodlights, can be aimed so that their beam lumens fall within an area, the over-all utilization factor is likely to be not more than .40.

* See Lamp Dept. Bulletins on lighting design.
** See "I.E.S. Standard Testing Specifications for Lighting Equipment."

To solve Formula B, after choosing the desired footcandles and estimating the maintenance and Utilization Factors, a size of floodlight is chosen for trial calculation and its Beam Lumens (from Table 15) are substituted in the equation.

When the dimensions or shape of an area point to the use of several types of floodlights--with different beam spreads, it is customary to divide the area into sections and plan a system for each of them. Buildings with setbacks are typical examples, also very tall structures such as towers or monuments. In setback buildings, you would design one setback at a time, selecting the type of floodlight most suited for each. With towers or monuments, a similar approach is in order.

EXAMPLE

A 300 ft. monument 60′ x 60′ at the base (Fig. 114) to be lighted to 5 footcandles might be divided into two sections—upper and lower—for purposes of calculation. With the distance D fixed or assumed, the first task would be to select the best floodlight type (beam spread) for each section, from the data in Table 12. The solution below is for one of four faces.

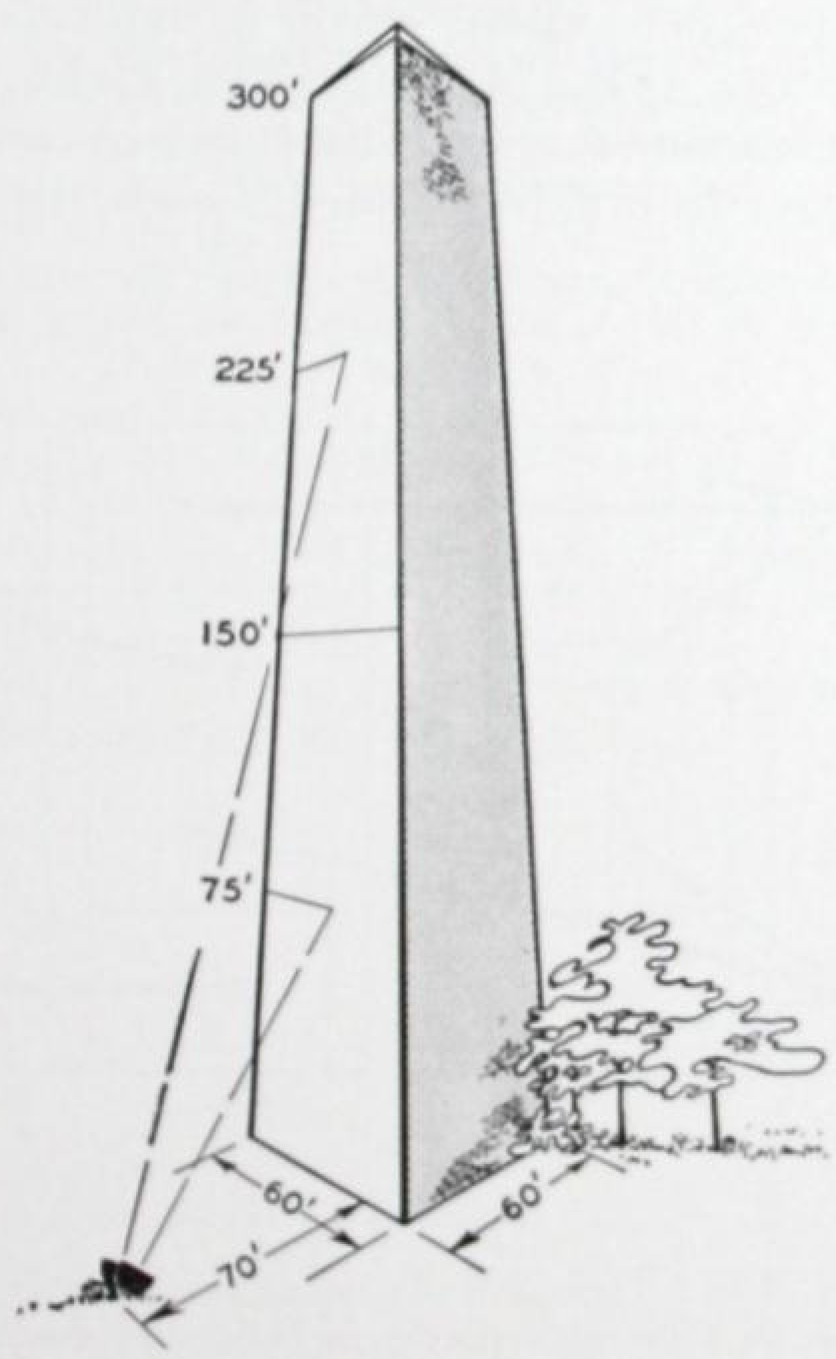


Fig. 114

Lower Section

With the floodlight aimed at the center of the lower section (75 ft. up) and at a distance D of 70 feet the average Aiming Angle would be about 45 degrees (Fig. 110). From Table 12, it is seen that the width of the spot from a 30° beam with a D of 70 feet at a 45° Aiming Angle, is 55.0 feet. The length or height of the spot, is 80.8 feet. (Area = 3493 sq. ft.) Since both of these dimensions fall with the bottom section limits (60 feet wide, 150 feet high), it can be assumed that the utilization factor of the floodlights for this section would follow conclusion 1, page 84, and equal .75 or better.

Solving Formula A, assuming a coverage factor of 2 (Table 13),

$$\text{30° Floodlights Needed for Coverage} = \frac{\text{Area Lighted x Coverage Factor}}{\text{Beam Spot Area}} = \frac{9000 \times 2}{3493} = 5.2 \text{ or } 5$$

Solving Formula B with 1000-watt—30° floodlights Table 15 shows it has 9600 beam lumens):

$$\text{1000-watt Floodlights Needed for Footcandles} = \frac{\text{Footcandles x Area}}{\text{MF x UF x Beam Lumens}} = \frac{5 \times 9000}{.7 \times .75 \times 9600} = 9$$

Nine 1000-watt 30° floodlights would serve the purpose with adequate coverage and the required footcandles.

Upper Section

In this section the average Aiming Angle is measured from the distance D of 70 feet and the height to the midpoint of 225 feet. From Fig. 110, this is found to be about 70 degrees. A 15° beam at D of 70 feet aimed at 70 degrees has a Width of 57.8 feet and a length (height) of 181 feet; the Spot Area is 8,232 square feet.

Solving Formula A, we have:

$$\text{15° Floodlights Needed for Coverage} = \frac{\text{Area Lighted x Coverage Factor}}{\text{Beam Spot Area}} = \frac{9000 \times 2}{8232} = 2.2 \text{ or } 2$$

Solving Formula B with 1500-watt floodlights (12,300 beam lumens), we have:

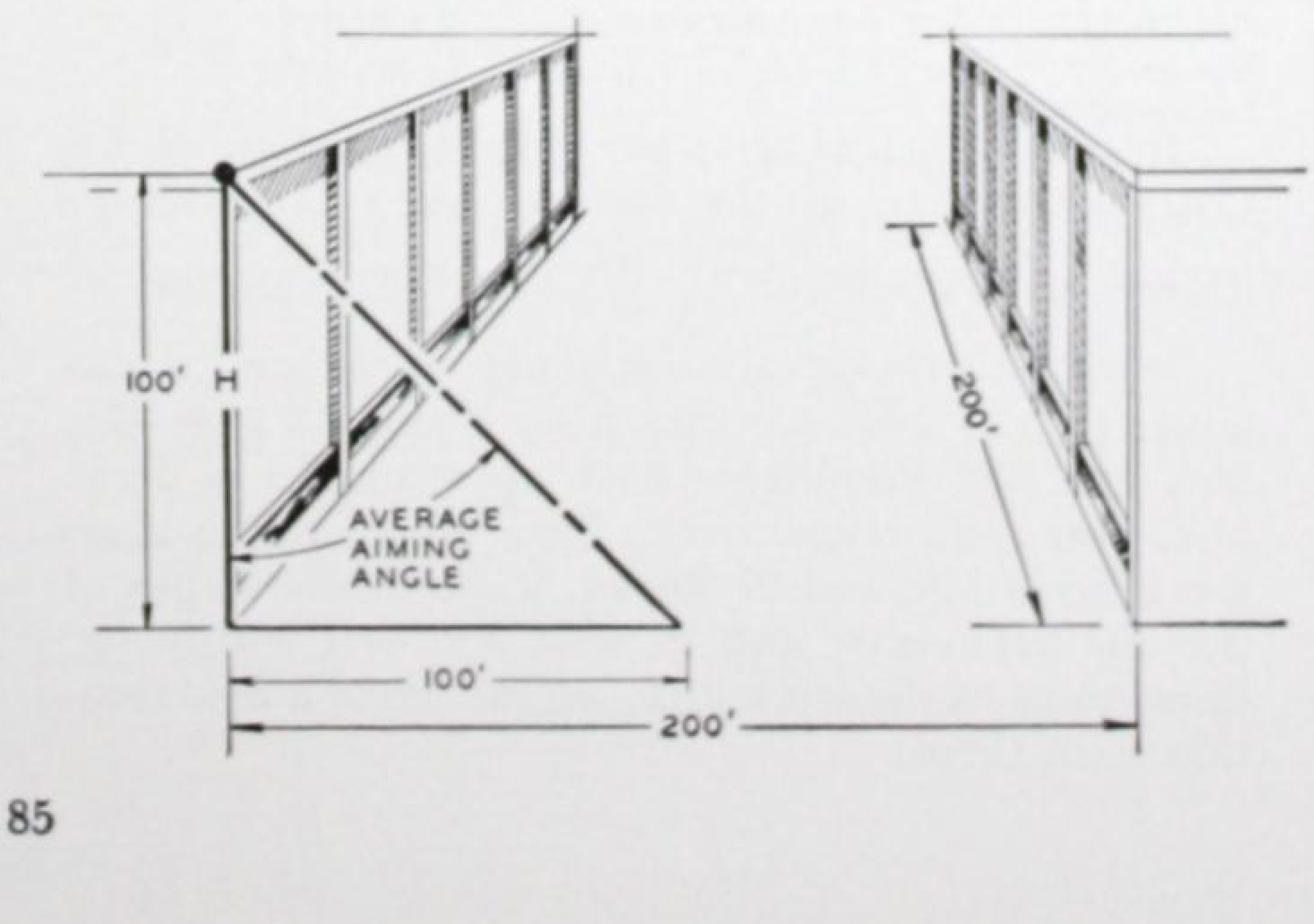
$$\text{1500-watt Floodlights Needed for Footcandles} = \frac{\text{Footcandles x Area}}{\text{MF x UF x Beam Lumens}} = \frac{5 \times 9000}{.7 \times .75 \times 12{,}300} = 7.0$$

Since these floodlights are the largest in the table, seven would be necessary.

Example

Assume that a construction area 200 feet by 200 feet in a steel mill yard is to be lighted to 5 footcandles by a perimeter system. It is located between two buildings each 100 feet high. A scale drawing or reference to the chart (Fig. 110) indicates an average aiming angle of 45°.

With an average aiming angle of 45° and a distance D of 100′ we find from Table 12 that 15°, 30°, and 50° floodlights have spot lengths of 53.6′ 115′, and 238′, respectively. The corresponding areas are 1,583, 7,129, and 27,900 sq. ft. Since the length of the 30° beam spot and its area are well within the dimensions



of the work area, we can make a trial solution with them:

Solving Formula A, assuming a coverage factor of 4 (Table 13),

$$\begin{array}{l}30^\circ\\ \text{Floodlights}\\ \text{Needed for}\\ \text{Coverage}\end{array} = \frac{\text{Area Lighted x Coverage Factor}}{\text{Beam Spot Area}} = \frac{40{,}000 \times 4}{7129} = 23$$

To solve Formula B, we assume a maintenance factor of .3 (extremely dirty location), a utilization factor of .7, and for trial assume the use of a 1500-watt floodlight (30°). Table 15 shows it has 15,700 beam lumens.

Solving Formula B,

$$\begin{array}{l}30^\circ\\ \text{Floodlights}\\ \text{Needed for}\\ \text{Footcandles}\end{array} = \frac{\text{Footcandles x Area}}{\text{MF x UF x Beam Lumens}} = \frac{5 \times 40{,}000}{.3 \times .7 \times 15{,}700} = 60$$

Since this number is greater than the number required for adequate coverage, we conclude that 60—1500-watt 30° beam floodlights would satisfactorily illuminate this construction area.

When the Floodlights Needed for Footcandles is found to be much *greater* than the Floodlights Needed for Coverage, recalculate using a *larger* luminaire if available (more beam lumens), consistent with other factors. As mentioned previously, the size may be restricted by other factors, such as bulk, weight, or an analysis of costs.

When the Floodlights Needed for Footcandles is found to be considerably *less* than the Floodlights Needed for Coverage, choose a *smaller* floodlight (less beam lumens) and recalculate Formula B, until a more reasonable number is reached. If this is impractical, choose a floodlight with a wider beam-spread.

Example

If a parking area of the same size (200′ x 200′) in a clean location (M.F. = .7) were to be lighted to 2 footcandles with 15° floodlights, Formula A would be:

$$\begin{array}{l}15^\circ\\ \text{Floodlights}\\ \text{Needed for}\\ \text{Coverage}\end{array} = \frac{\text{Area Lighted x Coverage Factor}}{\text{Beam Spot Area}} = \frac{40{,}000 \times 2}{1583} = 50$$

Solving Formula B, for a trial with 1500-watt floodlights, we have:

$$\begin{array}{l}\text{1500-watt}\\ \text{Floodlights}\\ \text{Needed for}\\ \text{Footcandles}\end{array} = \frac{\text{Footcandles x Area}}{\text{MF x UF x Beam Lumens}} = \frac{2 \times 40{,}000}{.7 \times .7 \times 12{,}300} = 13$$

Another trial using a small floodlight, say the 500-watt with 4300 beam lumens, would give:

$$\begin{array}{l}\text{500-watt}\\ \text{Floodlight}\\ \text{Needed for}\\ \text{Footcandles}\end{array} = \frac{\text{Footcandles x Area}}{\text{MF x UF x Beam Lumens}} = \frac{2 \times 40{,}000}{.7 \times .7 \times 4300} = 38$$

In this example, the 50 Floodlights Needed for Coverage can be of the 500-watt size. The average illumination would be $\frac{50}{38}$ x 5 or 6.6 footcandles.

With an average aiming angle of 45° and a distance (D) of 100′, we find from Table 12 that 15°, 30°, and 50° floodlights have spot lengths of 53.6′, 115′, and 238′, respectively. The corresponding areas are 1,583, 7,129, and 27,900 sq. ft. Since the length of the 30° beam spot and its area are well within the dimensions of the work area, we can make a trial solution with them:

Solving Formula A,

$$\begin{array}{l}30^\circ\\ \text{Floodlights}\\ \text{Needed for}\\ \text{Coverage}\end{array} = \frac{\text{Area Lighted x Coverage Factor}}{\text{Beam Spot Area}} = \frac{40{,}000 \times 4}{7129} = 23$$

To solve Formula B, we assume a maintenance factor of .3 (extremely dirty location), a utilization factor of .7, and for trial assume the use of a 1500-watt floodlight (30°). Table 15 shows it has 15,700 beam lumens.

Solving Formula B,

$$\begin{array}{l}30^\circ\\ \text{Floodlights}\\ \text{Needed for}\\ \text{Footcandles}\end{array} = \frac{\text{Footcandles x Area}}{\text{MF x UF x Beam Lumens}} = \frac{5 \times 50{,}000}{.3 \times .7 \times 15{,}700} = 60$$

Since this number is greater than the number required for adequate coverage, we conclude that 60—1500-watt 30° beam floodlight units would satisfactorily illuminate this construction area.

In construction and other areas, the activity may require high illumination levels on vertical surfaces. If so, some or all of the floodlights should be of the broad-beam type. From Table 15, it is seen that the beam-lumens of the two 1000-watt types—medium and broad-beam—are nearly the same. Hence, either or both types could be applied. Combinations of types are often used. A typical triple-tennis-court system (Fig. 115) includes eight broad-beam floodlights aimed toward the outer courts and four medium-beam luminaires aimed toward the center court.

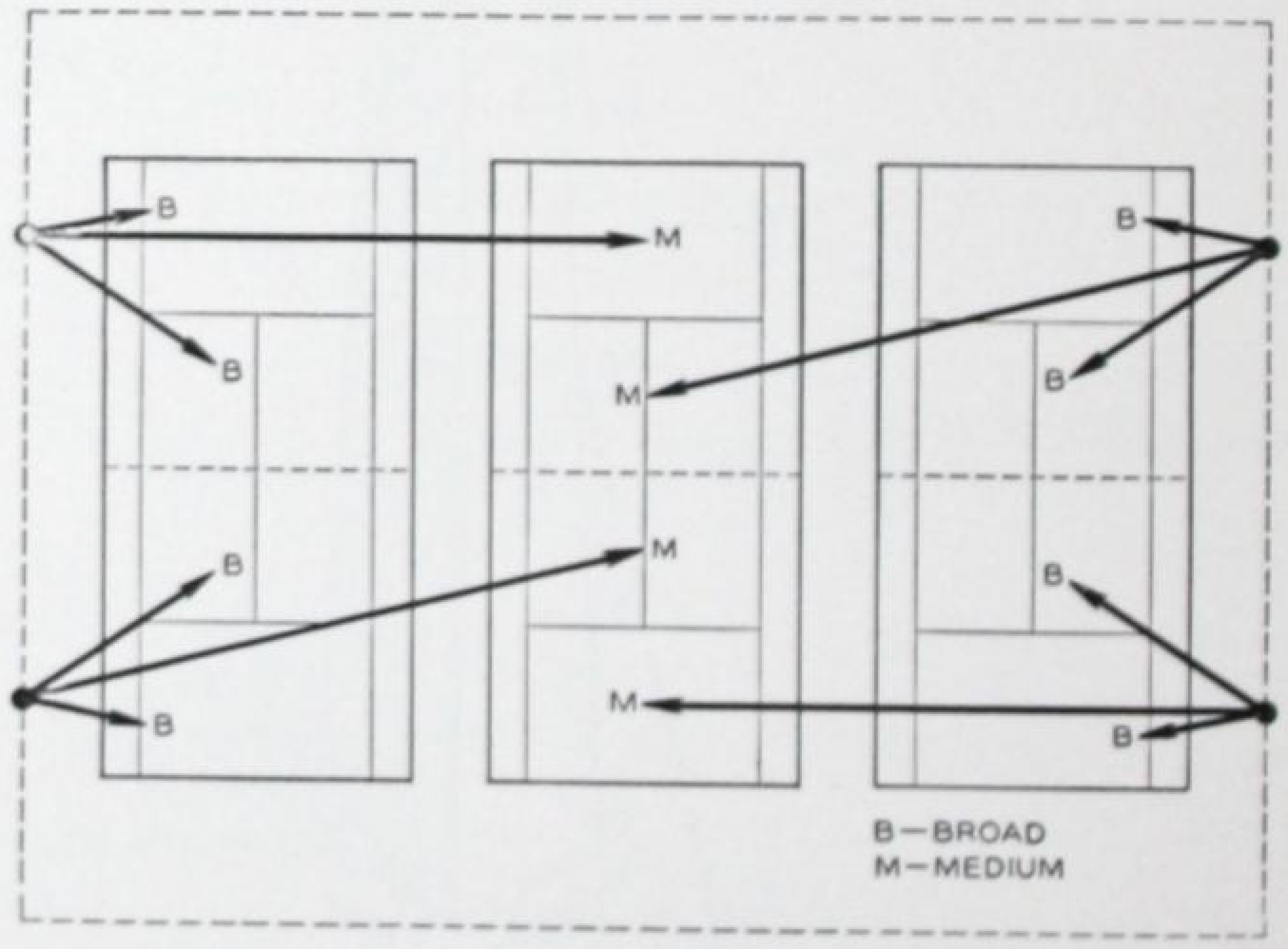


Fig. 115 Typical triple-tennis-court system, designed so that the line of sight of a player in following the ball seldom crosses the floodlight beam directly. The wide-beam floodlights are aimed toward the near courts; two medium-beam floodlights add extra light to the center area of the middle court.

In applying the beam-lumens method and other methods, parts of areas may still have low footcandles. This may be due to obstructions, limitations on pole locations, or longer throws than the floodlights chosen can handle. When such occur, build up the areas involved by relocating some luminaires, if possible. Distant areas may also be helped by supplementary narrow-beam floodlights aimed toward the spot. However, in many installations substantially uniform lighting is not necessarily preferable. The *seeing needs* of any area are, in the final analysis, the principal determinants.

Plotting Floodlight Spot Areas

With the chart of Fig. 110 and a scale drawing of the area to be lighted, it is relatively simple to plot the approximate spot areas of floodlights. Such plotting aids in determining the best choice of floodlight type and the time spent may easily prove economical in the long run. A complete plot, such as partly shown in Fig. 117, can be made in the following steps:

1. Draw the boundaries of the area to a convenient scale.
2. Find L and W for floodlights aimed at the corners and overlapped ¼ of their beam spots as follows:
   a. Assume that the beam axis of a floodlight is pointed at the boundary (position a, Fig. 113). From the chart of Fig. 110 and the distance D and H (measure these on your scale drawing) find the "trial" aiming angle. **Subtract 5° from it for a narrow-beam floodlight, 10° for a 30° beam; 20° for a 50° beam; the answer is the final Aiming Angle.** Entering Table 12, find the L and W for the beam selected at that Aiming Angle.
   b. On thin paper, draw the ellipse with dimensions L and W by the method of Fig. 116. Next draw quartering lines on the template and after cutting it out, apply it to the scale drawing and trace the outlines as shown, lapping the beam spots one-quarter each way (or more).

In Fig. 117, a 15° floodlight at a D of 20 ft. with its axis pointed at the left far corner of the field has an H of 56 ft. and a trial aiming angle of 70° (similar to position a, Fig. 113). Subtracting 5° leaves 65° as the final Aiming Angle. With a D of 20 ft. and an Aiming Angle of 65°, Table 12 shows a 15° Beam to spread to an L of 32 ft. and a W of 13.0 ft. This spot drawn by the method of Fig. 116 is shown dotted in the far left corner with its far quarter-point at the corner.

Assume point C, the near quarter point of this 15° spot, as the "boundary" of the inner row of floodlights mounted at A (and B), a 50° floodlight at A with the axis pointed at C (similar to position a, Fig. 113) would show a trial aiming angle of 63° (from D = 20 ft., H = 40 ft., Fig. 110). Subtracting 20° from 63° leaves 43° as the final Aiming Angle. A 50° Beam at a D of 20 ft. and an Aiming Angle of 43° is seen in Table 12 to have an L of about 44 ft. and a W of 27 ft. This spot is plotted in the near left corner of the field.

The center spots are 30° Beam Spots. With a D of 20 ft. and H equal to 50 ft. (aiming at the far boundary), the trial aiming angle is 63° (from Fig. 110). Subtracting 10° leaves 53°, the final Aiming Angle. A 30° beam with a D of 20 ft. and an Aiming Angle of 53° is seen in Table 12 to have an L of 30 ft. and a W of about 18 ft. The Beam Spot is shown in the middle group with the quarter-point on the far boundary.

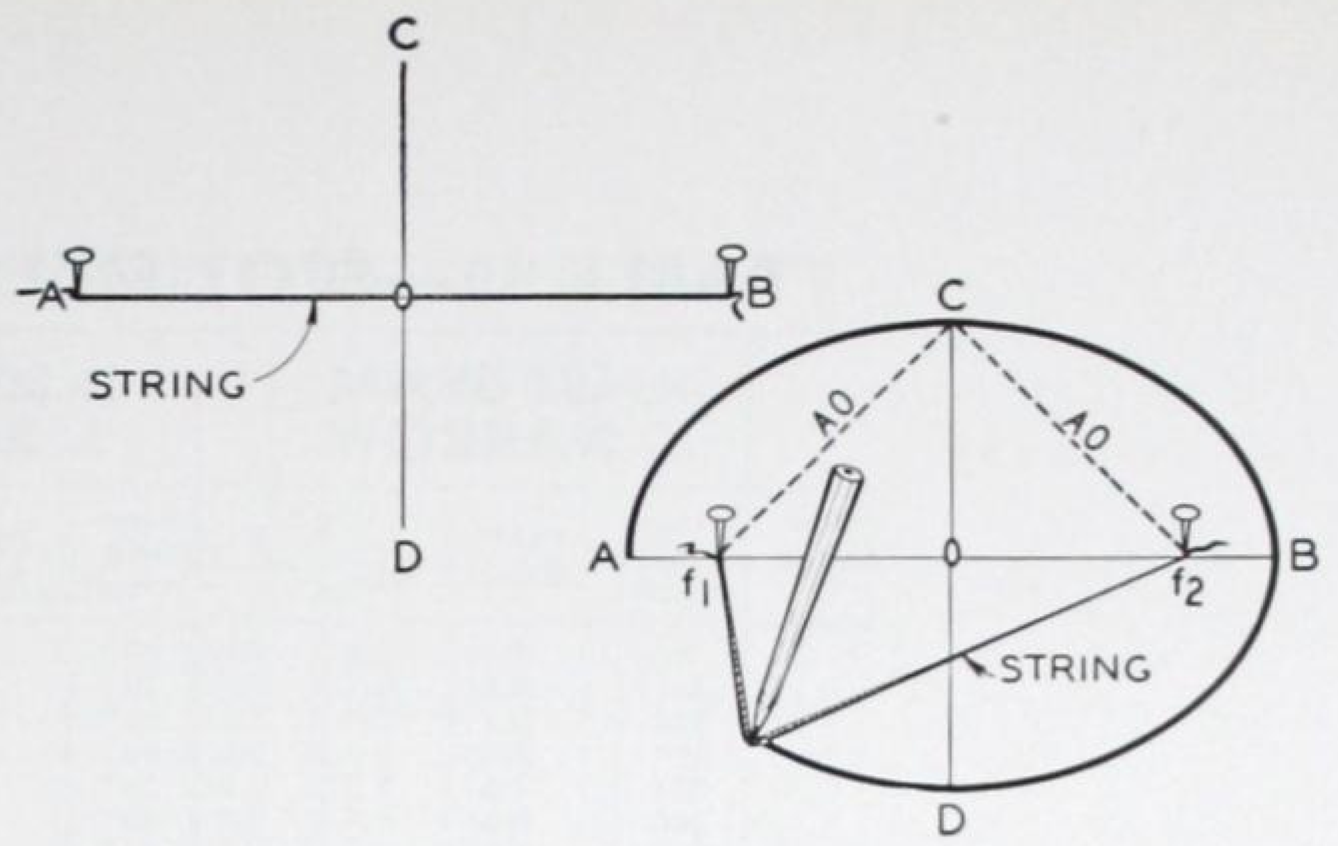


Fig. 116 Drawing an ellipse with a compass and string.

Step 1—With values L and W from Table 12, draw lines A-B and C-D bisecting each other as shown (left). With a compass setting equal to A-O and with C as the center, mark points f1 and f2 on line A-B.

Step 2—Fasten two pins at A and B, then tie a string between them. Remove the string and pins together and reset the pins at the points f1 and f2. With a sharp pencil draw in the ellipse as illustrated (right).

A 30° floodlight aimed to overlap one-quarter of the far 30° floodlight beam (similar to the 15° and 50° beams) has a trial aiming angle of 58° (from D = 20 ft., H = 32 ft.). Subtracting 10° leaves 48° as the final Aiming Angle. From Table 12, we find that for these dimensions L = 24 ft. and W = 16 ft. The beam spot is shown in the center near position. Study of the left and central beam spots—leads to the final choice of 30° beams for the far row and 50° floodlights for the near row. These are respectively plotted in the right corner along B-C."

For the far-right corner 30° beam, the trial aiming angle is 70° (from D = 20 ft., H = 56 ft.). Subtracting 10° leaves 60° as the final Aiming Angle. A 30° beam with a D of 20 ft. and a 60° Aiming Angle has an L of 54.6 and a W of 24.1 ft. (Table 12).

The trial aiming angle for the 50° floodlight aimed at C" with D = 20 ft. and H = 27.5 ft. is 53°. Subtracting 20° leaves 33° as the final Aiming Angle. A 50° beam at a 33° Aiming Angle with a D of 20 ft. indicates an L of 27.5 and a W of 23 ft. The spot is shown on the sketch (near right) with the ¾ point at C."

3. To complete the layout, dot in the other beam spots, overlapping them at the quarter-points. Duplicate groups of floodlights on the far boundary at points similar to A and B would complete the system.

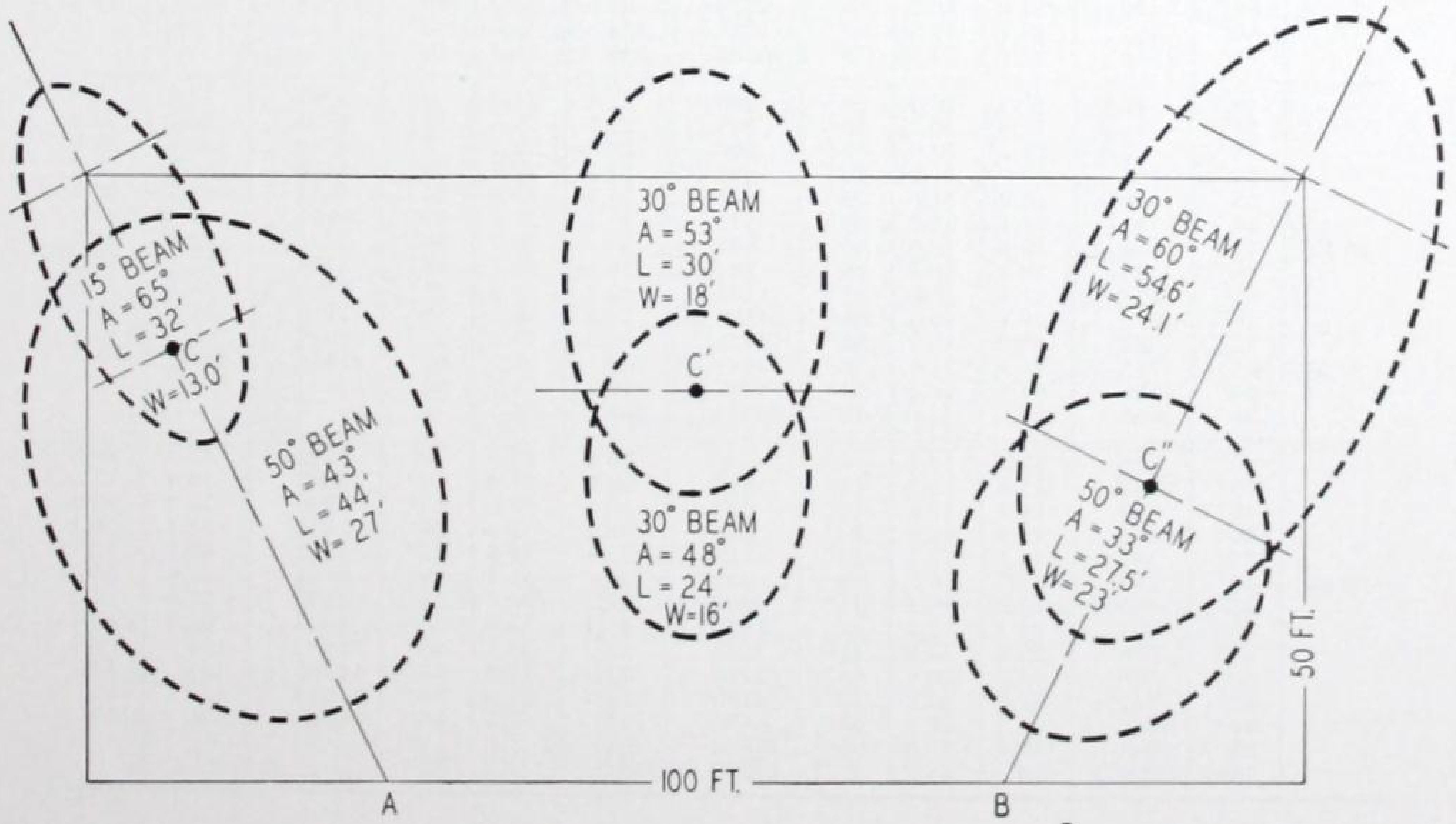


Fig. 117 Narrow-beam floodlights aimed toward the corners of the area overlap the boundaries ¼ of their beam spots. See Fig. 113. Broadbeam floodlights illuminate the near part of the area and overlap the perimeter similarly. A similar system (not shown) would be installed on the far boundary. Drawing the spots on a scale-drawing help in selecting the best type for the purpose.

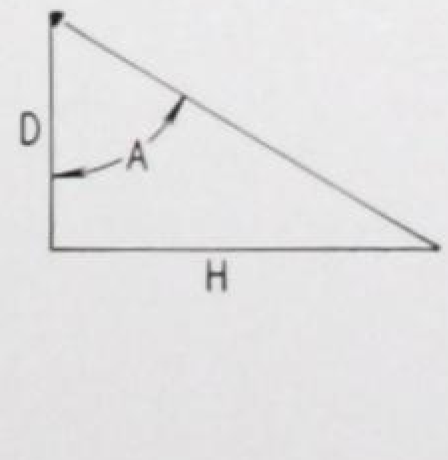


TABLE 12—SPOT SIZES—FLOODLIGHT BEAMS

	15° BEAM NARROW				30° BEAM MEDIUM				50° BEAM BROAD			
Distance D	Aiming Angle	SPOT AREA	L Ft.	W Ft.	Aiming Angle	SPOT AREA	L Ft.	W Ft.	Aiming Angle	SPOT AREA	L Ft.	W Ft.
10 Ft.	0°	5.4	2.6	2.6	0°	22.5	5.4	5.4	0°	68.3	9.3	9.3
	10°	5.7	2.7	2.7	10°	23.7	5.5	5.4	10°	72.2	9.7	9.5
	15°	6.1	2.8	2.7	15°	25.2	5.8	5.6	15°	77.6	10.2	9.7
	20°	6.6	3.0	2.8	20°	27.6	6.1	5.7	20°	86.0	10.9	10.1
	25°	7.3	3.2	2.9	25°	31.0	6.6	6.0	25°	98.8	11.9	10.6
	30°	8.5	3.5	3.0	30°	36.0	7.3	6.3	30°	118	13.4	11.2
	35°	10.0	4.0	3.2	35°	43.3	8.3	6.7	35°	147	15.6	12.0
	40°	12.3	4.5	3.5	40°	54.2	9.6	7.2	40°	195	18.8	13.2
	45°	15.8	5.4	3.8	45°	71.3	11.5	7.9	45°	279	23.8	14.9
	50°	21.1	6.5	4.1	50°	99.8	14.4	8.8	50°	448	32.7	17.5
	55°	30.4	8.3	4.7	55°	152	19.1	10.1	55°	871	50.9	21.8
	60°	47.2	11.1	5.4	60°	259	27.3	12.1	60°	2651	107	31.5
	65°	81.6	16.0	6.5	65°	545	44.8	15.5	65°			
	70°	168	25.9	8.3	70°	1809	100	23.0	70°			
15 Ft.	0°	12.3	3.9	3.9	0°	50.6	8.0	8.0	0°	154	14.0	14.0
	10°	12.8	4.1	4.0	10°	53.3	8.3	8.2	10°	162	14.5	14.2
	15°	13.6	4.2	4.1	15°	56.7	8.7	8.3	15°	175	15.2	14.6
	20°	14.8	4.5	4.2	20°	62.0	9.2	8.6	20°	193	16.3	15.1
	25°	16.5	4.8	4.4	25°	69.8	9.9	8.9	25°	222	17.9	15.8
	30°	19.0	5.3	4.6	30°	81.1	11.0	9.4	30°	265	20.1	16.8
	35°	22.5	5.9	4.8	35°	97.5	12.4	10.0	35°	331	23.3	18.1
	40°	27.7	6.8	5.2	40°	122	14.4	10.8	40°	439	28.1	19.8
	45°	35.6	8.0	5.6	45°	160	17.3	11.8	45°	628	35.7	22.3
	50°	47.6	9.8	6.2	50°	224	21.7	13.2	50°	1008	49.0	26.2
	55°	68.5	12.4	7.0	55°	341	28.6	15.2	55°	1961	76.4	32.7
	60°	106	16.7	8.1	60°	582	41.0	18.1	60°	5965	161	47.2
	65°	184	24.0	9.7	65°	1226	67.2	23.2	65°			
	70°	378	38.8	12.4	7C°	4070	150	34.5	70°			
20 Ft.	0°	21.8	5.3	5.3	0°	90.0	10.7	10.7	0°	273	18.6	18.6
	10°	22.8	5.4	5.3	10°	94.8	11.1	10.9	10°	289	19.4	19.0
	15°	24.2	5.7	5.5	15°	101	11.5	11.1	15°	310	20.3	19.5
	20°	26.3	6.0	5.6	20°	110	12.2	11.5	20°	344	21.7	20.1
	25°	29.4	6.4	5.8	25°	124	13.3	11.9	25°	395	23.8	12.1
	30°	33.8	7.1	6.1	30°	144	14.6	12.5	30°	471	26.8	22.4
	35°	40.	7.9	6.5	35°	173	16.6	13.3	35°	588	31.1	24.1
	40°	49.2	9.1	6.9	40°	217	19.2	14.3	40°	780	37.5	26.5
	45°	63.3	10.7	7.5	45°	285	23.1	15.7	45°	1116	47.7	29.8
	50°	84.6	13.1	8.3	50°	399	28.9	17.6	50°	1792	65.3	34.9
	55°	122	16.6	9.3	55°	606	38.2	20.2	55°	3486	102	43.6
	60°	189	22.2	10.8	60°	1035	54.6	24.1	60°	10604	215	62.9
	65°	327	32.0	13.0	65°	2179	89.6	31.0	65°			
	70°	672	51.8	16.5	70°	7236	200	46.1	70°			
30 Ft.	0°	49.0	7.9	7.9	0°	202	16.1	16.1	0°	615	28.0	28.0
	10°	51.3	8.1	8.0	10°	213	16.6	16.3	10°	650	29.0	28.5
	15°	54.5	8.5	8.2	15°	227	17.3	16.7	15°	698	30.5	29.2
	20°	59.1	9.0	8.4	20°	248	18.4	17.2	20°	774	32.6	30.2
	25°	66.1	9.6	8.7	25°	279	19.9	17.9	25°	889	35.8	31.6
	30°	76.1	10.6	9.1	30°	324	22.0	18.8	30°	1059	40.2	33.5
	35°	90.0	11.9	9.7	35°	390	24.8	20.0	35°	1324	46.7	36.1
	40°	111	13.6	10.4	40°	488	28.8	21.5	40°	1755	56.3	39.7
	45°	142	16.1	11.3	45°	642	34.6	23.6	45°	2511	71.5	44.7
	50°	190	19.6	12.4	50°	898	43.3	26.4	50°	4033	98.0	52.4
	55°	274	24.9	14.0	55°	1364	57.2	30.3	55°	7843	153	65.3
	60°	425	33.3	16.2	60°	2329	82.0	36.2	60°	23859	322	94.4
	65°	735	48.1	19.5	65°	4903	134	46.5	65°			
	70°	1512	77.7	24.8	70°	16282	300	16.1	70°			
40 Ft.	0°	87.2	10.5	10.5	0°	360	21.4	21.4	0°	1093	37.3	37.3
	10°	91.2	10.9	10.7	10°	379	22.1	21.8	10°	1155	38.7	38.0
	15°	97.0	11.3	10.9	15°	403	23.1	22.2	15°	1242	40.6	38.9
	20°	105	12.0	11.0	20°	441	24.5	22.9	20°	1376	43.5	40.3
	25°	118	12.9	11.6	25°	496	26.5	23.8	25°	1581	47.7	42.2
	30°	135	14.1	12.2	30°	576	29.3	25.1	30°	1883	53.6	44.7
	35°	160	15.8	12.9	35°	693	33.1	26.7	35°	2354	62.2	48.2
	40°	197	18.2	13.8	40°	867	38.5	28.7	40°	3120	75.1	52.9
	45°	253	21.4	15.0	45°	1141	46.2	31.4	45°	4464	95.3	59.6
	50°	338	26.1	16.5	50°	1596	57.8	35.2	50°	7170	131	69.9
	55°	487	33.2	18.7	55°	2426	76.3	40.5	55°	13942	204	87.1
	60°	755	44.4	21.6	60°	4141	109	48.2	60°	42416	429	126
	65°	1306	64.1	26.0	65°	8717	179	61.9	65°			
	70°	2688	104	33.0	70°	28946	400	92.1	70°			
50 Ft.	0°	136	13.2	13.1	0°	562	26.8	26.8	0°	1707	46.6	46.6
	10°	142	13.6	13.3	10°	592	27.7	27.2	10°	1805	48.4	47.5
	15°	151	14.1	13.6	15°	629	28.8	27.8	15°	1940	50.8	48.6
	20°	164	14.9	14.0	20°	689	30.6	28.6	20°	2150	54.4	50.3
	25°	184	16.1	14.5	25°	775	33.1	29.8	25°	2470	59.6	52.7
	30°	211	17.7	15.2	30°	901	36.6	31.3	30°	2942	67.0	55.9
	35°	250	19.8	16.1	35°	1083	41.4	33.3	35°	3677	77.8	60.2
	40°	307	22.7	17.3	40°	1355	48.1	35.9	40°	4875	93.8	66.1
	45°	396	26.8	18.8	45°	1782	57.7	39.3	45°	6975	119	74.5
	50°	529	32.7	20.6	50°	2494	72.2	44.0	50°	11202	163	87.3
	55°	761	41.5	23.3	55°	3790	95.4	50.6	55°	21785	255	109
	60°	1180	55.5	27.0	60°	6470	137	60.3	60°	66275	536	157
	65°	2041	80.1	32.4	65°	13620	224	77.4	65°			
	70°	4200	129	41.3	70°	45227	500	115	70°			

TABLE 12 (Continued)

	15° BEAM NARROW				30° BEAM MEDIUM				50° BEAM BROAD			
Distance D	Aiming Angle	SPOT AREA	L Ft.	W Ft.	Aiming Angle	SPOT AREA	L Ft.	W Ft.	Aiming Angle	SPOT AREA	L Ft.	W Ft.
	0°	196	15.8	15.8	0°	810	32.1	32.1	0°	2459	56.0	56.0
	10°	205	15.3	16.0	10°	853	33.2	32.7	10°	2599	58.1	57.0
	15°	218	16.9	16.4	15°	906	34.6	33.3	15°	2794	60.9	58.4
	20°	236	17.9	16.8	20°	992	36.8	34.4	20°	3096	65.2	60.4
	25°	265	19.3	17.5	25°	1117	39.8	35.7	25°	3557	71.5	63.3
60 Ft.	30°	305	21.2	18.3	30°	1297	43.9	37.6	30°	4237	80.4	67.1
	35°	360	23.7	19.4	35°	1560	49.7	40.0	35°	5296	93.3	72.2
	40°	443	27.2	20.8	40°	1951	57.7	43.0	40°	7020	113	79.4
	45°	570	32.1	22.6	45°	2566	69.3	47.2	45°	10044	143	89.4
	50°	761	39.2	24.8	50°	3592	86.7	52.8	50°	16132	196	105
	55°	1095	49.8	28.0	55°	5458	114	60.7	55°	31370	306	131
	60°	1699	66.7	32.5	60°	9317	164	72.4	60°	95436	644	189
	65°	2939	96.1	38.9	65°	19613	269	92.9	65°			
	70°	6048	155	49.6	70°	65128	600	138	70°			
	0°	267	18.4	18.4	0°	1102	37.5	37.5	0°	3347	65.3	65.3
	10°	279	19.0	18.7	10°	1161	38.8	38.1	10°	3538	67.8	66.5
	15°	297	19.8	19.1	15°	1234	40.4	38.9	15°	3802	71.1	68.1
	20°	322	20.9	19.6	20°	1351	42.9	40.1	20°	4214	76.1	70.5
	25°	360	22.5	20.4	25°	1520	46.4	41.7	25°	4841	83.4	73.8
	30°	414	24.7	21.3	30°	1765	51.2	43.9	30°	5767	93.8	78.3
70 Ft.	35°	490	27.7	22.6	35°	2123	57.9	46.6	35°	7208	109	84.3
	40°	603	31.8	24.2	40°	2656	67.3	50.2	40°	9555	131	92.6
	45°	776	37.5	26.3	45°	3493	80.8	55.0	45°	13671	167	104
	50°	1036	45.7	28.9	50°	4889	101	61.6	50°	21957	229	122
	55°	1491	58.1	32.7	55°	7428	134	70.8	55°	42699	357	152
	60°	2313	77.8	37.9	60°	12681	191	84.4	60°	129899	751	220
	65°	4001	112	45.4	65°	26695	314	108	65°			
	70°	8232	181	57.8	70°	88646	700	161				
	0°	349	21.1	21.1	0°	1440	42.9	42.9	0°	4371	74.6	74.6
	10°	365	21.7	21.4	10°	1517	44.3	43.6	10°	4621	77.4	76.0
	15°	388	22.6	21.8	15°	1611	46.2	44.4	15°	4966	81.2	77.8
	20°	420	23.9	22.4	20°	1764	49.0	45.8	20°	5504	87.0	80.6
	25°	470	25.7	23.3	25°	1985	53.0	47.7	25°	6323	95.3	84.4
	30°	541	28.2	24.4	30°	2306	58.6	50.1	30°	7533	107	89.4
80 Ft.	35°	640	31.7	25.8	35°	2773	66.2	53.3	35°	9414	124	96.3
	40°	787	36.3	27.7	40°	3469	76.9	57.4	40°	12480	150	105
	45°	1013	42.9	30.1	45°	4563	92.4	62.9	45°	17866	191	119
	50°	1354	52.3	33.0	50°	6386	115	70.4	50°	28678	261	140
	55°	1947	66.4	37.4	55°	9702	153	80.9	55°	55770	407	174
	60°	3021	88.9	43.3	60°	16563	219	96.5	60°	169664	858	252
	65°	5226	128	51.9	65°	34867	358	124	65°			
	70°	10752	207	66.1	70°	115782	800	184				
	0°	441	23.7	23.7	0°	1822	48.2	48.2	0°	5532	83.9	83.9
	10°	462	24.4	24.0	10°	1920	49.8	49.8	10°	5848	87.1	85.5
	15°	491	25.4	24.6	15°	2040	51.9	50.0	15°	6286	91.4	87.6
	20°	532	26.9	25.2	20°	2233	55.1	51.6	20°	6966	97.9	90.6
	25°	595	29.0	26.2	25°	2513	59.6	53.6	25°	8003	107	94.9
90 Ft.	30°	685	31.8	27.4	30°	2918	65.9	56.4	30°	9534	121	101
	35°	810	35.6	29.1	35°	3510	74.5	60.0	35°	11915	140	108
	40°	996	40.9	31.1	40°	4390	86.6	64.6	40°	15795	169	119
	45°	1282	48.2	33.8	45°	5774	104	70.8	45°	22599	214	134
	50°	1713	58.8	37.2	50°	8082	130	79.2	50°	36296	294	157
	55°	2465	74.7	42.0	55°	12280	172	91.0	55°	70583	458	196
	60°	3823	100	48.7	60°	20963	246	108	60°	214731	966	283
	65°	6614	144	58.4	65°	44129	403	139	65°			
	70°	13608	233	74.3	70°	146537	900	207	70°			
	0°	545	26.3	26.3	0°	2250	53.6	53.6	0°	6830	93.3	93.3
	10°	570	27.2	26.7	10°	2370	55.4	54.5	10°	7220	96.8	95
	15°	606	28.2	27.3	15°	2518	57.7	55.6	15°	7760	101	97.3
	20°	657	29.9	28.0	20°	2757	61.3	57.3	20°	8600	109	101
	25°	735	32.2	29.1	25°	3102	66.3	59.6	25°	9880	119	105
	30°	846	35.3	30.5	30°	3603	73.2	62.7	30°	11770	134	112
100 Ft.	35°	1000	39.6	32.3	35°	4333	82.8	66.6	35°	14710	156	120
	40°	1230	45.4	34.6	40°	5420	96.2	71.7	40°	19500	188	132
	45°	1583	53.6	37.6	45°	7129	115	78.6	45°	27900	238	149
	50°	2115	65.3	41.3	50°	9978	144	88.0	50°	44810	327	175
	55°	3043	83.0	46.7	55°	15160	191	101	55°	87140	509	218
	60°	4720	111	54.1	60°	25880	273	121	60°	265100	1073	315
	65°	8165	160	64.9	65°	54480	448	155	65°			
	70°	16800	259	82.6	70°	180910	1000	230				

Note:

To use this table for other D distances, the Spot Areas are proportional to the squares of the distance D involved. For example, for a D of 250 feet, the Spot Area would be $\frac{250^2}{100^2}$ or 6.25 times the table value for a D of 100 feet. The values of L and W are directly proportional to the D values. An L or W at a distance D of 250 feet is 2.5 times the table value at a D of 100 feet.

Table 13 — Typical Recommended Footcandle Levels and Coverage Factors for Floodlighting Systems

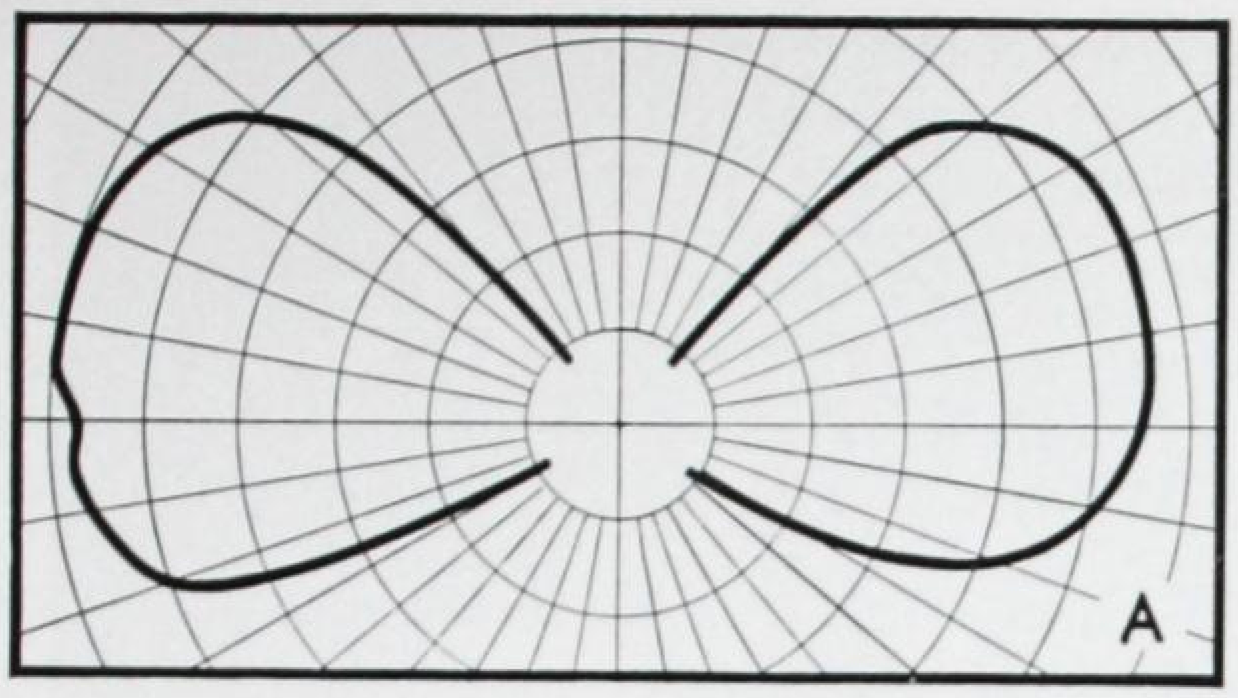
LOCATION	Foot-candles	Minimum Coverage Factor
Buildings — Average Surroundings	10–30	2
Construction Work	5	3–4
Fences	0.2	1–2
Gas Stations	10–30	3–4
Loading Platforms	5–10	3–4
Parking Lots	1–2	2
Protective Lighting — Active Areas	5–50	2
Shipyards — construction	5–10	3–4
Signs, Poster Boards	20–100	1–2
Trees, Monuments	5–20	1–2

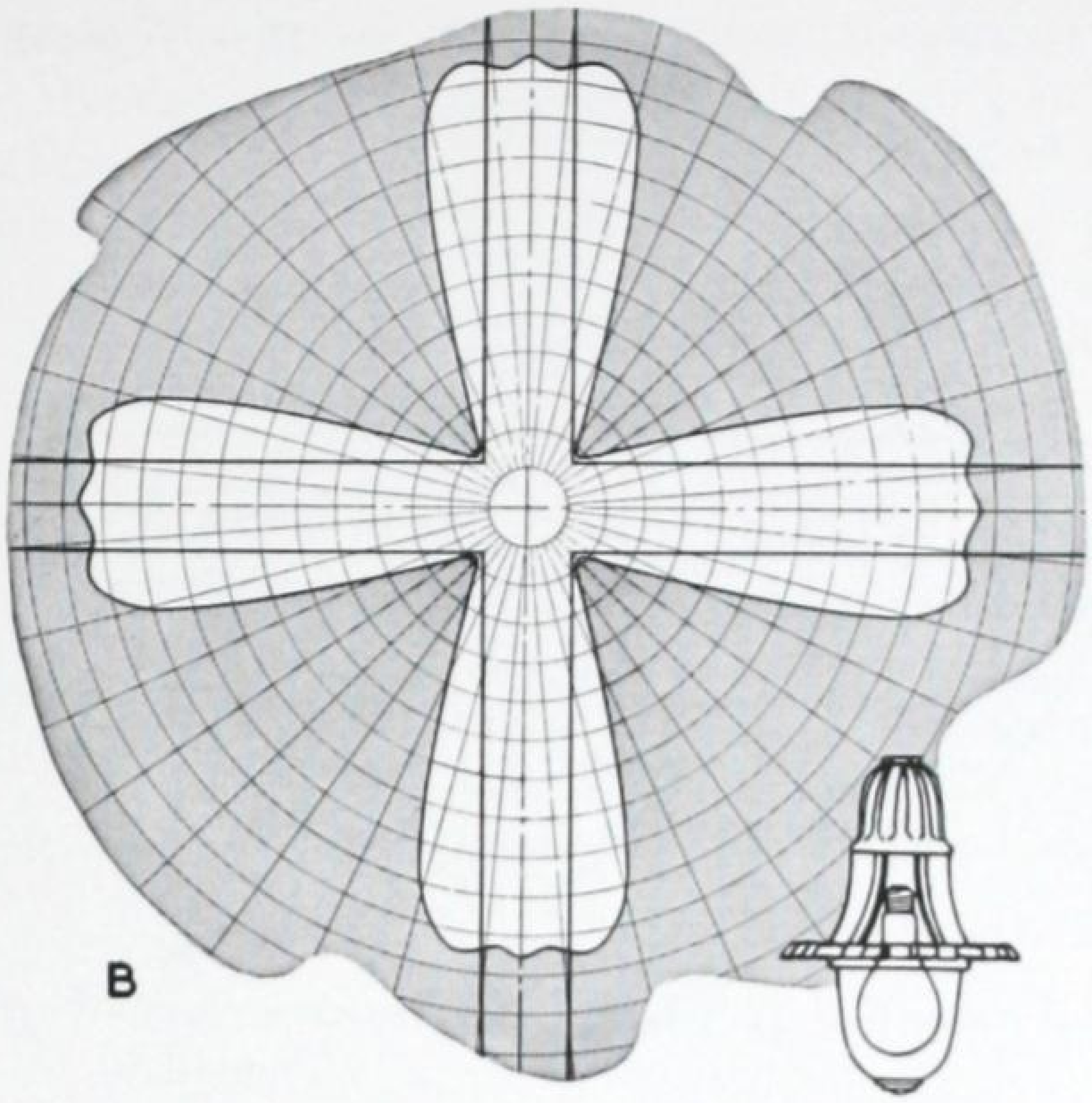
Table 14 — Floodlight Beam Spread for Typical Areas

Type of Area	Approx. Distance to Area	Beam Spread
Buildings 2-3 story lighted from curb posts	10′–30′	Broad, also Fresnel type (wide spread)
Buildings lighted from across street		
A. Areas 3000 sq. ft. or less	50′–100′	Broad or Medium
B. Areas 3000 sq. ft. to 10,000 sq. ft.	50′–100′	Medium or Narrow
Construction work, Parking spaces	At perimeter	Broad or Medium
Baseball, Football	Behind bleachers	Broad and Medium

Table 15 — Approximate Beam Lumens of Typical Floodlight Luminaires

15° Beam (Narrow)		30° Beam (Medium)		50°–60° Beam (Broad)	
Floodlight Lamp Size	Beam Lumens	General Service Lamp Size	Beam Lumens	General Service Lamp Size	Beam Lumens
250-watt	1300	200-watt	1,400	500-watt	3900–5100
500-watt	3400–4300	500-watt	4,300		
		750-watt	7,100	750-watt	6750– 8,100
1000-watt	7600–9500	1000-watt	9,600	1000-watt	9100–10,900
1500-watt	12,300	1500-watt	15,700		
		150 PAR-38 Spot	600	150 PAR-38 Flood	1400
200 PAR-46 (16° x 23°)	1600	300 PAR-56 Flood (20° x 35°)	1,900		





B

Fig. 118. Asymmetric curves of a kerosene lamp (A) and a four-way refractor-type street lighting unit (B).

STREET LIGHTING

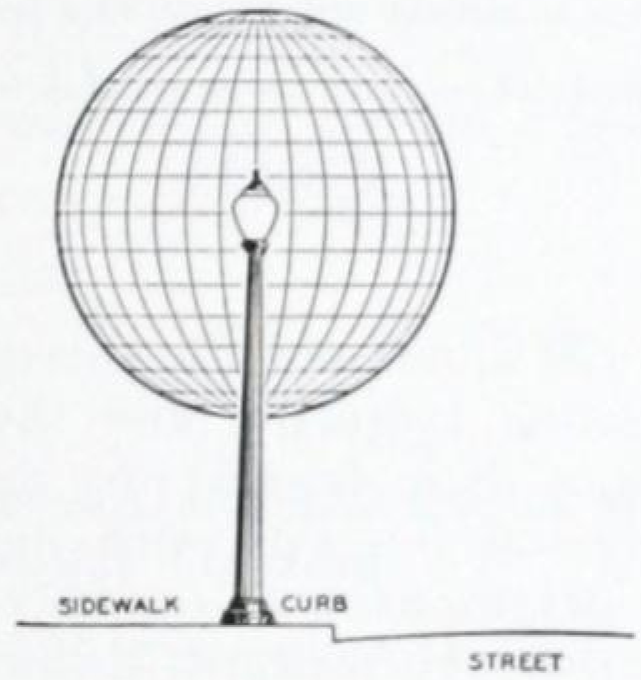
ISOCANDLE CURVES

Lighting units which produce asymmetrical distribution are old in the art of illumination, an example of one of the older forms is the kerosene lamp. A modern example is the asymmetric refractor unit of the design used at the intersection of two streets. Conventional candlepower distribution curves of these two sources are shown in Fig. 118.

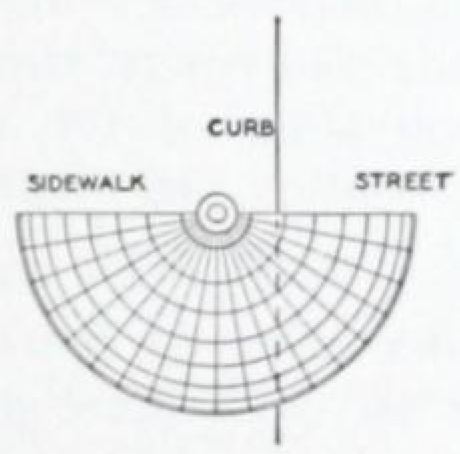
The "ideal" way to plot the photometric distribution of an asymmetrical unit would be on the surface of a large sphere centered on the unit*. The sphere could be ruled off in degrees of latitude and longitude like a globe of the world, and the light received by each section could be indicated. But since most such data require a more simple and reproducible form for general use, a curve or curves on spherical-web plotting paper similar to that used by cartographers is utilized. On this form the lines of longitude are projected sine curves of various amplitudes, and the lines of latitude become equally-spaced horizontal lines. The theoretical spherical surface is seen in Fig. 119 to be transformed into a plane surface through the progressive steps—a, b, c, and d, and the light distribution of the unit graphically presented in *isocandle* (or equi-candle) curves. In illustration d, the vertical axis represents the plane parallel to the street, and the extreme boundaries of the chart, the plane crosswise of the street.

In practice, in order to plot isocandle curves for an asymmetrical lighting unit, it is necessary to obtain candlepower curves in a number of vertical planes at regular intervals (customarily of ten degrees) and select from these curves the angles at which they cross the 100-candle, 200-candle, etc., lines and plot the points on a spherical-web diagram, joining the points to complete the curves.

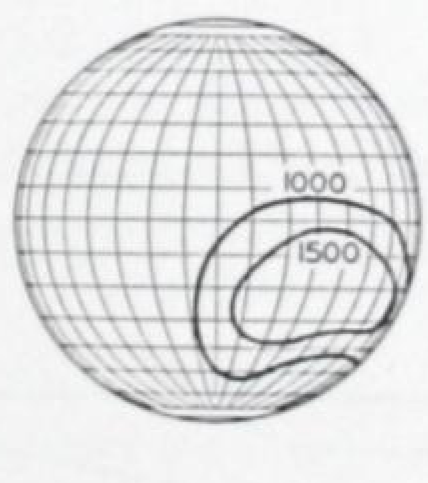
* See Transactions of the Illuminating Engineering Society, 1926, p. 135 (Benford).



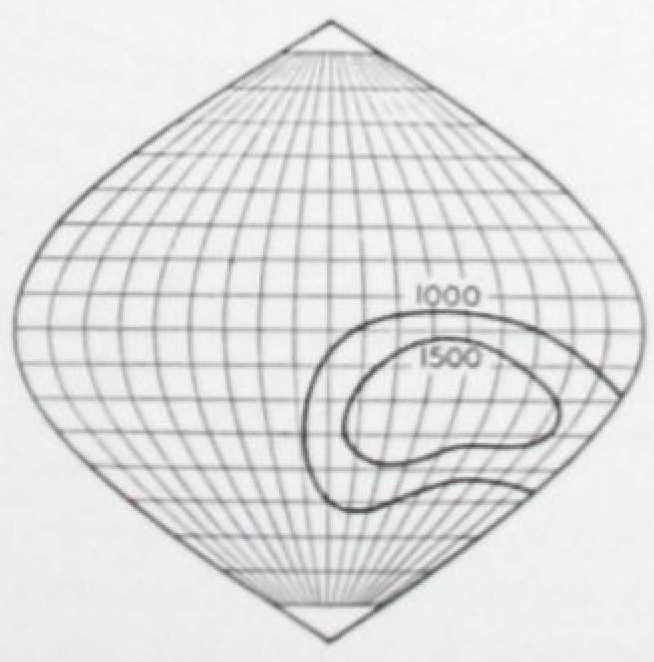
a. Imagine a hemispherical shell placed about the lamp as a center with its open side at right angles to the street.



b. Top view of hemisphere and unit.



c. On the hemisphere a curve is drawn joining the points representing a value of 1000 candles, another is shown at 1500 candles.



d. The hemisphere is then flattened to make it simple to reproduce on paper as the isocandle-web.

Fig. 119. Development of an isocandle-web chart.

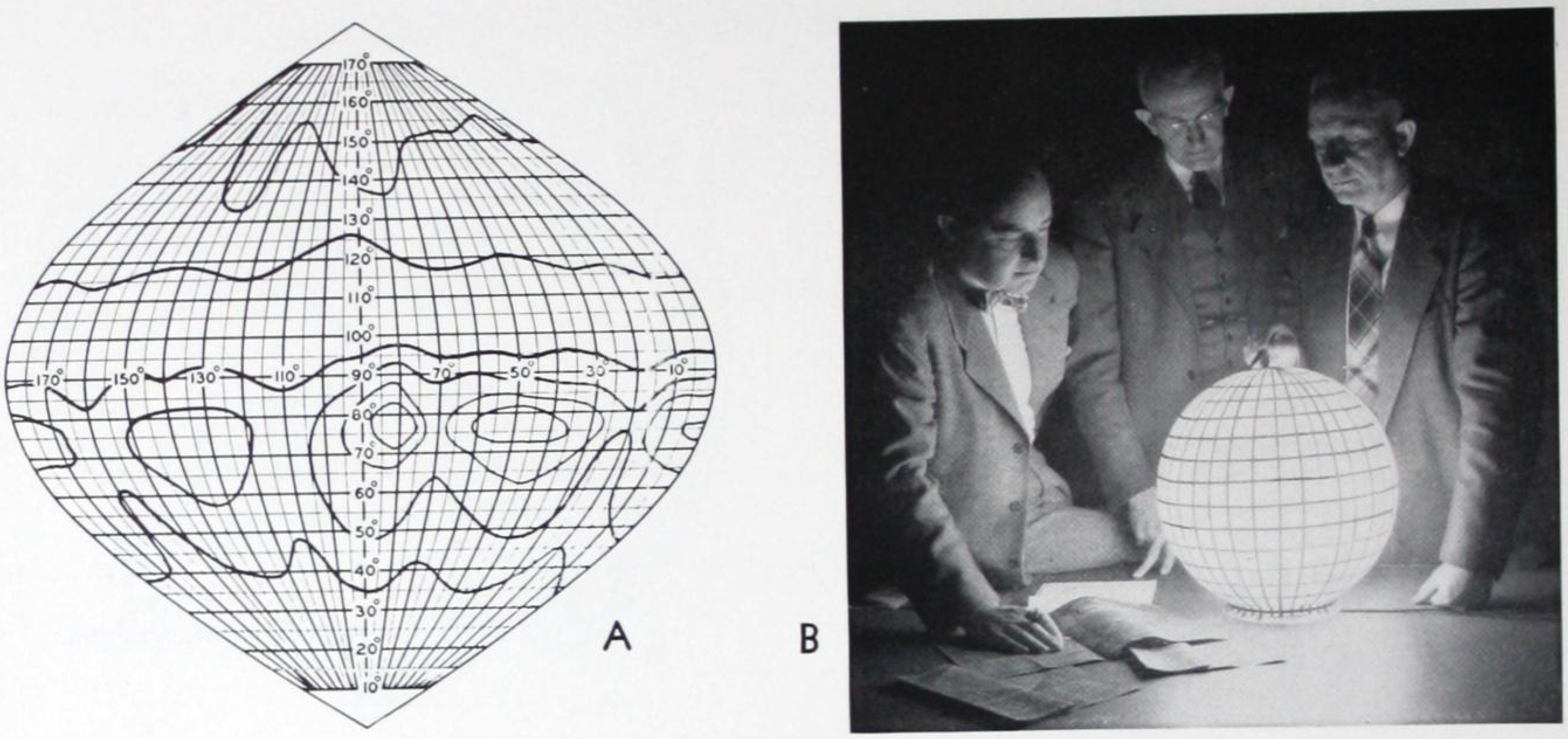


Fig. 120. A — Typical isocandle distribution of a lantern-type street lighting luminaire

B — Lighted sphere with degree-scales used in preparing isocandle curves of street-lighting fixtures.

The illustrations of Fig. 120 show isocandle curves of a lantern-type street lighting luminaire and the artist's conception of the same data showing the regions of low and high luminous intensity with the zones shaded in steps. The development of asymmetric lighting units was a distinct step forward in illuminating engineering, but along with the development came added complications in the photometry and calculations involved in the application of the units. Particularly in street lighting studies, the isocandle-web charts were very useful in plotting data.

A second form called *isolux lines of horizontal footcandles* (Fig. 121) further serves to show graphically the distribution of light from a system of street lighting standards. It is common practice in preparing these diagrams to choose representative points on the surface of the street along a series of parallel lines and then compute the horizontal illumination at each point from each of the sources, employing the point-by-point method (page 71), then adding the component values to obtain the total illumination at each point. The problems of computation are considerably involved, particularly with asymmetric distributions.

Such determinations are greatly facilitated by means of nomographs.

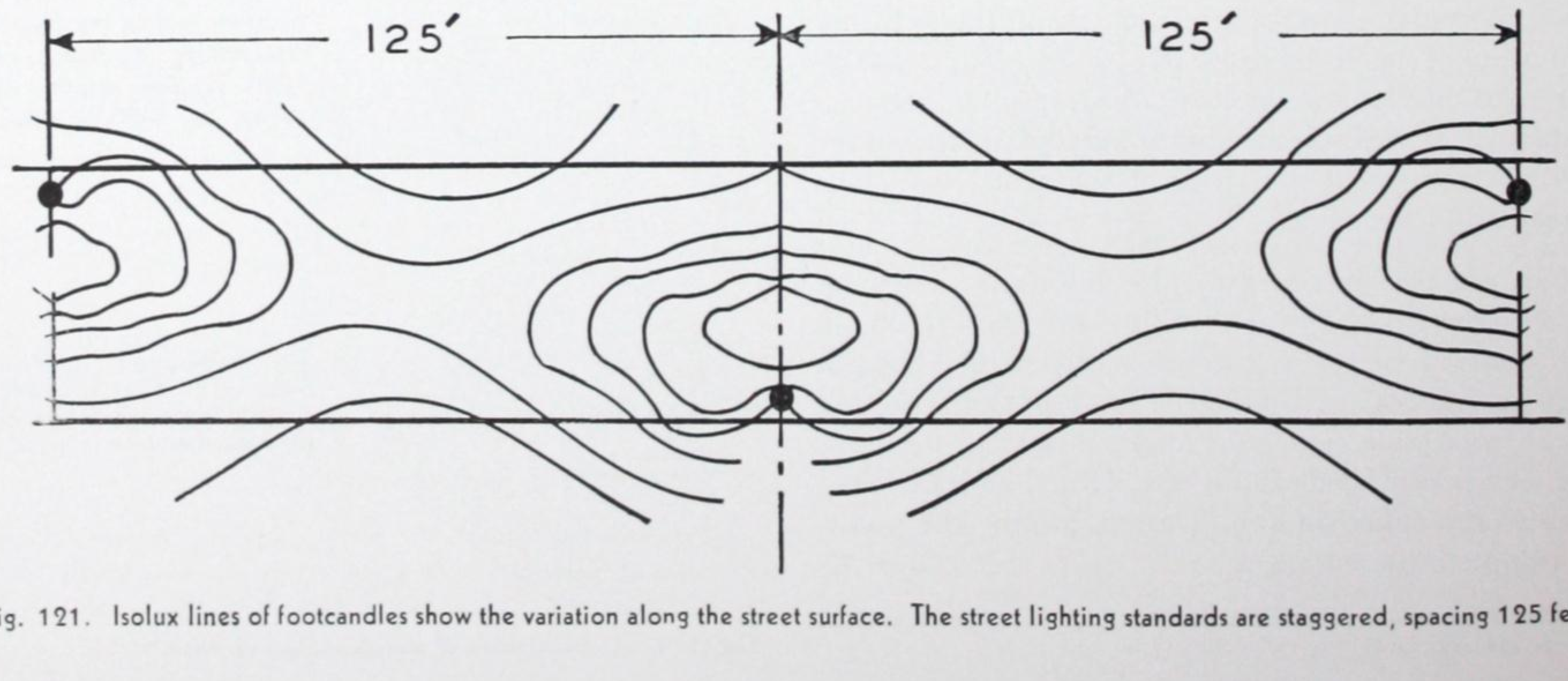


Fig. 121. Isolux lines of footcandles show the variation along the street surface. The street lighting standards are staggered, spacing 125 feet.

NOMOGRAPHS FOR LIGHTING CALCULATIONS

The nomograph in its simplest form is a graphical plot of data so aligned in a group of interrelated scales that by applying a straight-edge to connect two of the known quantities, the projection to the third scale indicates the value of the third (unknown). The set of nomographs* (following page 89) cover all the computations necessary to predetermine the horizontal and various vertical illumination values for a convenient range of distances and mounting heights. **Because of their logarithmic scales, these can be used for such widely different applications as street lighting, flood and sports lighting, posterboard and show window lighting, and similar installations.** Three types of nomographs are included in order to combine accuracy with a compact form. The square nomographs make use of an axis line in order to transfer from one set of data to another.

In the nomographs any pair of linear scales such as V and H of Chart II or any pair of illumination scales such as E_h and E_{v_n} may be multiplied by any common factor to secure extended range or greater accuracy. The same is true of the I and E_h scales of Chart III. The scales of angles, however, cannot be so treated.

Angular Relations

The sketch of Fig. 122 shows a street-lighting unit mounted at the curb. The determination of the horizontal and three vertical illumination values at the point P involve the following:

V—Vertical height of the unit above the road

H—Horizontal distance from the point P to the line parallel to the curb through the light-center

h—horizontal angle between R-S and R-P

v—vertical angle between the lines G-R and G-P

L—distance from the point R to P

D—distance from the point P to S

I—candlepower of the unit in the direction of the point P.
The determination of the angles v and h locates this value of candlepower on the curve of the unit, such as the isocandle curve of Fig. 124.

Use of the Charts

The procedure in using the charts is as follows:

Step 1—The *horizontal angle* h is found from Chart I.
D and H give h

Step 2—The *vertical angle* v is found from Chart II.
V and h give X,
H and X give v

Step 3—The *candlepower* I, corresponding to the angles h and v, is found from the curves of the unit, as in Fig. 124. Then the horizontal illumination E_H is found from Chart III.
I and v give X,
V and X give E_H

Three different values of vertical illumination may be obtained from the charts. The three vertical planes are shown in Fig. 123 and are termed $v_{n\ (normal)}$, v_l (lengthwise), and v_c (crosswise).

Step 4—The *vertical illumination* E_{v_n} is found from Chart IV.
E_H and v give E_{v_n}

Step 5—The *vertical illumination* E_{v_l} is found from Chart V.
V and H give X,
E_H and X give E_{v_l}

Step 6—The *vertical illumination* E_{v_c} is found from Chart VI.
E_H and D give X,
V and X give E_{v_c}

Example of the Use of the Charts—Street Lighting

Assume the luminaire used is one whose isocandle web chart is that of Fig. 124. The unit is mounted 25 feet above the road at the vertical distance V and at the curb. Consider a point on the surface of the road such that H equals 20 feet and D equals 75 feet.

Step 1—In Chart I, place a straight-edge across the values for H and D, then the horizontal angle h is found to be 75°. Since 75 ft. is off scale, use 2.0 and 7.5, read 75°).

Step 2—In Chart II, place the straight-edge across h (75°) and V (25). Mark the intersection on the diagonal line x. Then turn the straight-edge so that it crosses this point and H (20 ft.), continuing to the v scale. The value of the vertical angle v is 72°.

Step 3—From Fig. 124, the candlepower I is found by locating h = 75° on the horizontal axis, h-h. Then follow down this line vertically to the 72° point. This must be estimated between the 70° and 75° lines. The value is 1200 cp (I). On Chart III, project a line from I (1200) and v (72°) and mark the intersection on the diagonal line x. Then place the straight-edge from V (25 ft.) through the point on x to the E_H scale which reads .054 footcandles, which is the horizontal illumination at the point P.

Step 4—To obtain the vertical illumination on the plane v_n which is normal (at right angles) to the line L, use Chart IV. Project a line from E_H (.054) to v (72°), the intersection on E_{v_n} is .17 footcandles.

* From "Graphical Illumination Computations," by Russell C. Putnam, General Electric Review, December, 1933.

Step 5—To find the vertical illumination on the plane v_l which is lengthwise of the street, use Chart V. Place the straight-edge from V (25 ft.) through H (20 ft.), and mark the intersection on x. Then project from E_H (.054) through x to E_{v_l}, which gives the value of .043 footcandles. (Since the values are so small, use 5.4, read 4.3, divided by 100.)

Step 6—To obtain the vertical illumination on the plane v_c, which is at right angles to the street, use Chart VI. Trace a line from E_H (.054) to D (75 ft.), and mark the point on x. Then from V (25 ft.) through the point on x, find E_{v_c}, which is the value of .16 footcandles.

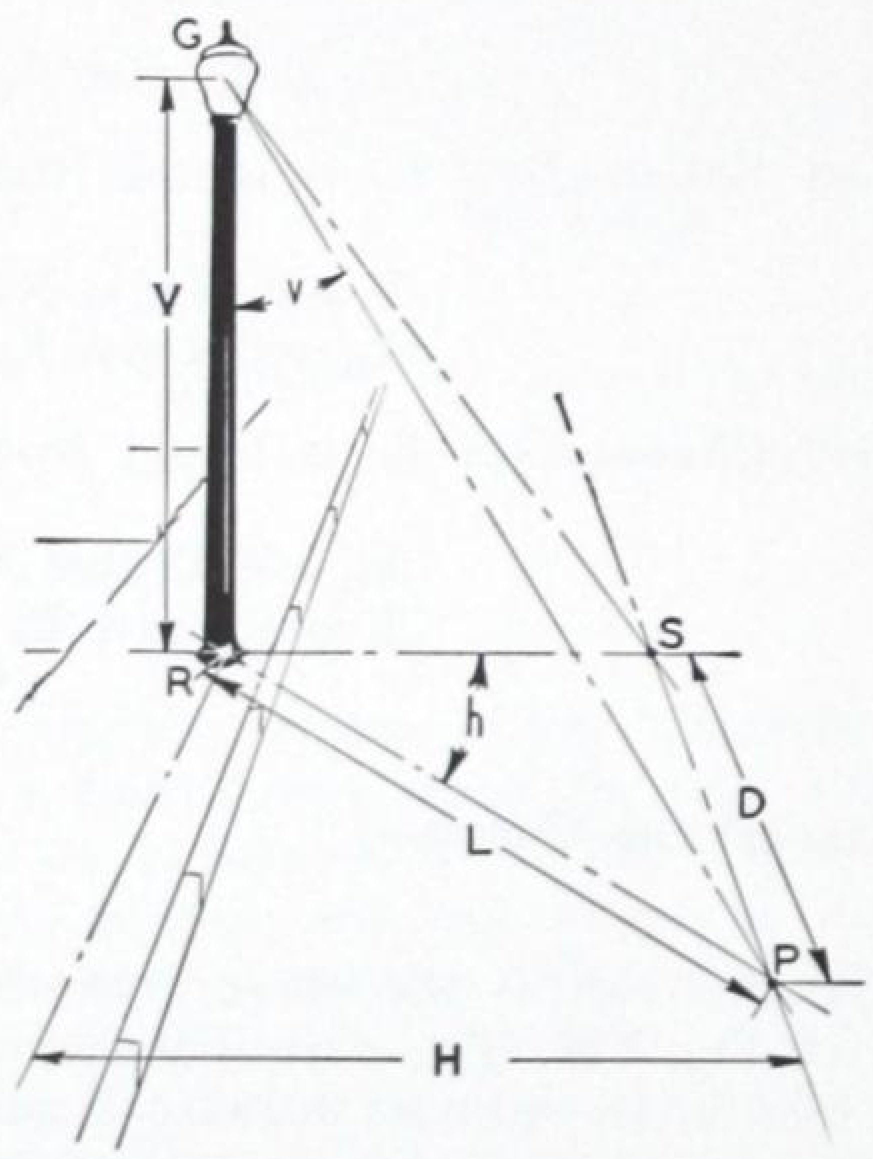


Fig. 122. Geometrical relationship between a street-lighting unit and any illuminated point P on the street surface.

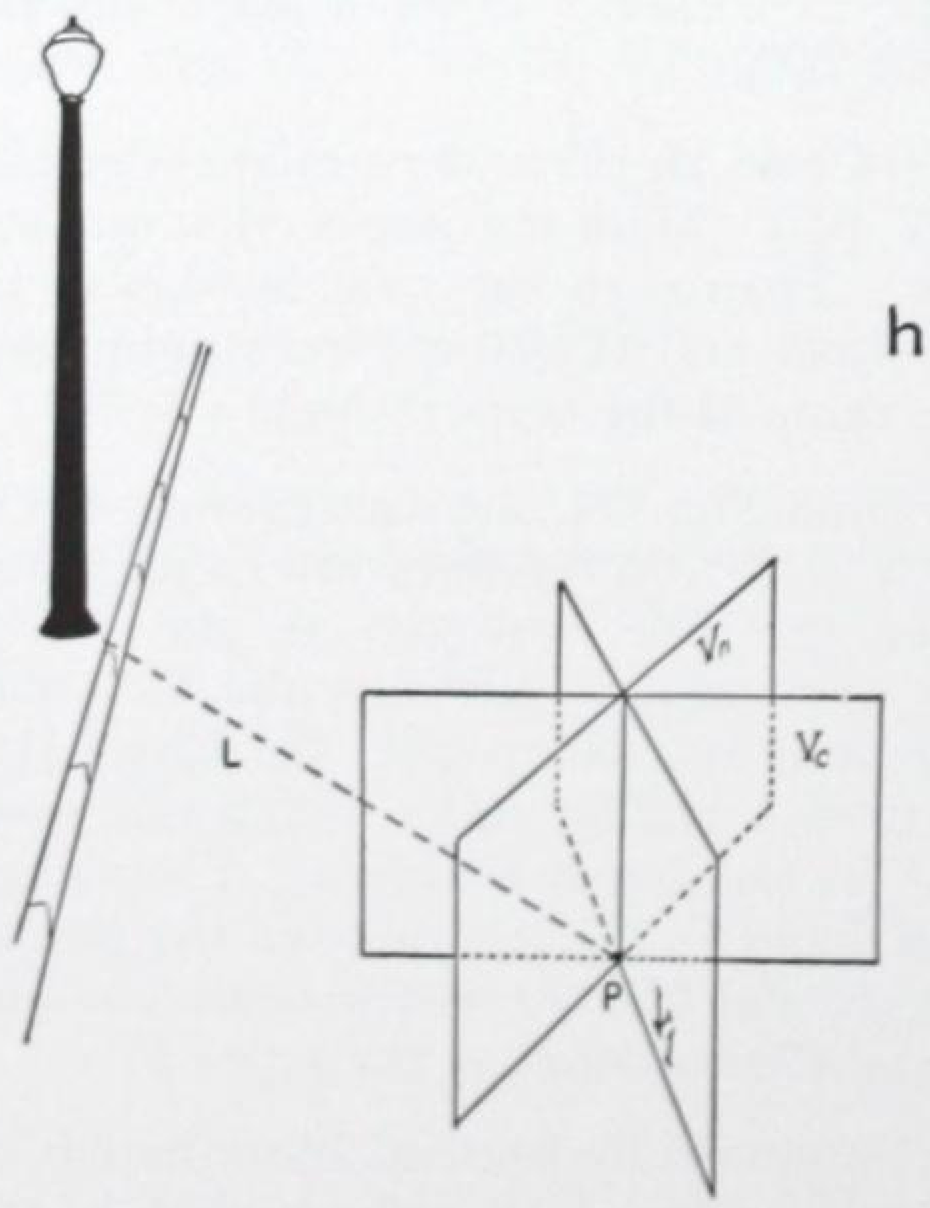


Fig. 123. Planes are Vl (lengthwise), Vc (crosswise), and Vn (normal).

For the case in which the horizontal illumination at S is desired, it may be seen from Fig. 122, that the horizontal angle h is 0°, and therefore Step 1 is omitted and Chart I is not used.

Step 2—on Chart II, place the straight-edge from V (25 ft.) to h (0°) and mark x. Then from H (20 ft.) and x, find v, which is 38°.

Step 3—On the isocandle web chart of Fig. 124, find the candlepower I corresponding to the angles h (0°) and v (38°), the value is 400 (I). On Chart III, project from I (400) and v (38°), and mark x. Then from V (25 ft.) through x, locate the value of E_H, which is .28 footcandles.

Examining the vertical planes v_n, v_l and v_c at the point S, it may be seen from Fig. 123 that v_n coincides with v_l, and therefore either Chart IV or V may be used. Since v_c is radial, the vertical illumination on it is zero and therefore Step 6 is also omitted.

Using Chart IV, connect E_H (.28 ft-c.) through v (38°), read E_{v_n} at .22 ft-c. Using Chart V, connect V (25 ft.) and H (20 ft.) and mark x. Then from E_H (.28 ft-c.) and x, read E_{v_l} at .22 ft-c. (Use 2.8 and x, read 2.2, divide by 10.)

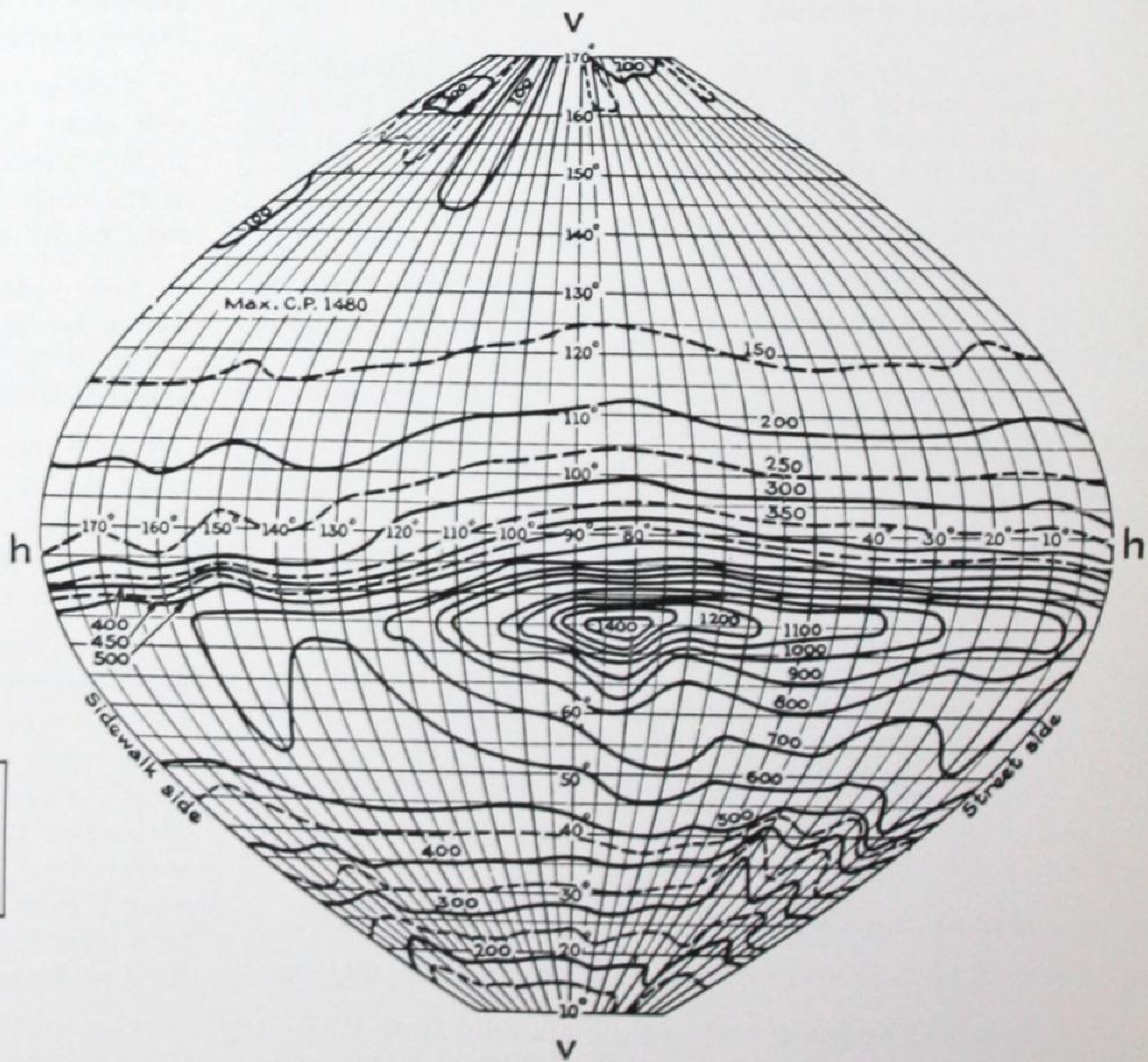


Fig. 124. Isocandle curves of a typical street-lighting luminaire.

NOMOGRAPHS FOR LIGHTING CALCULATIONS

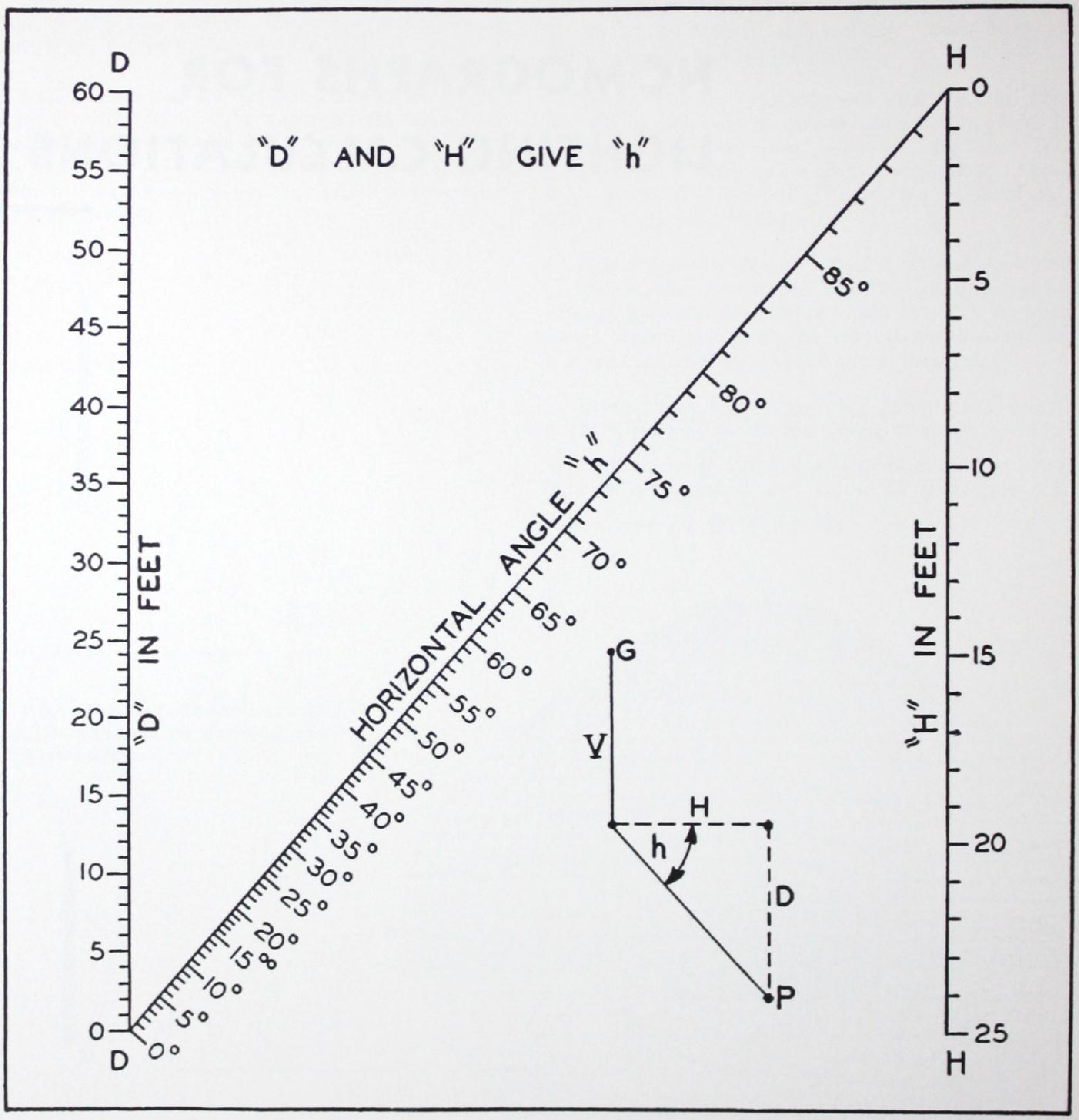


CHART I Horizontal Angle

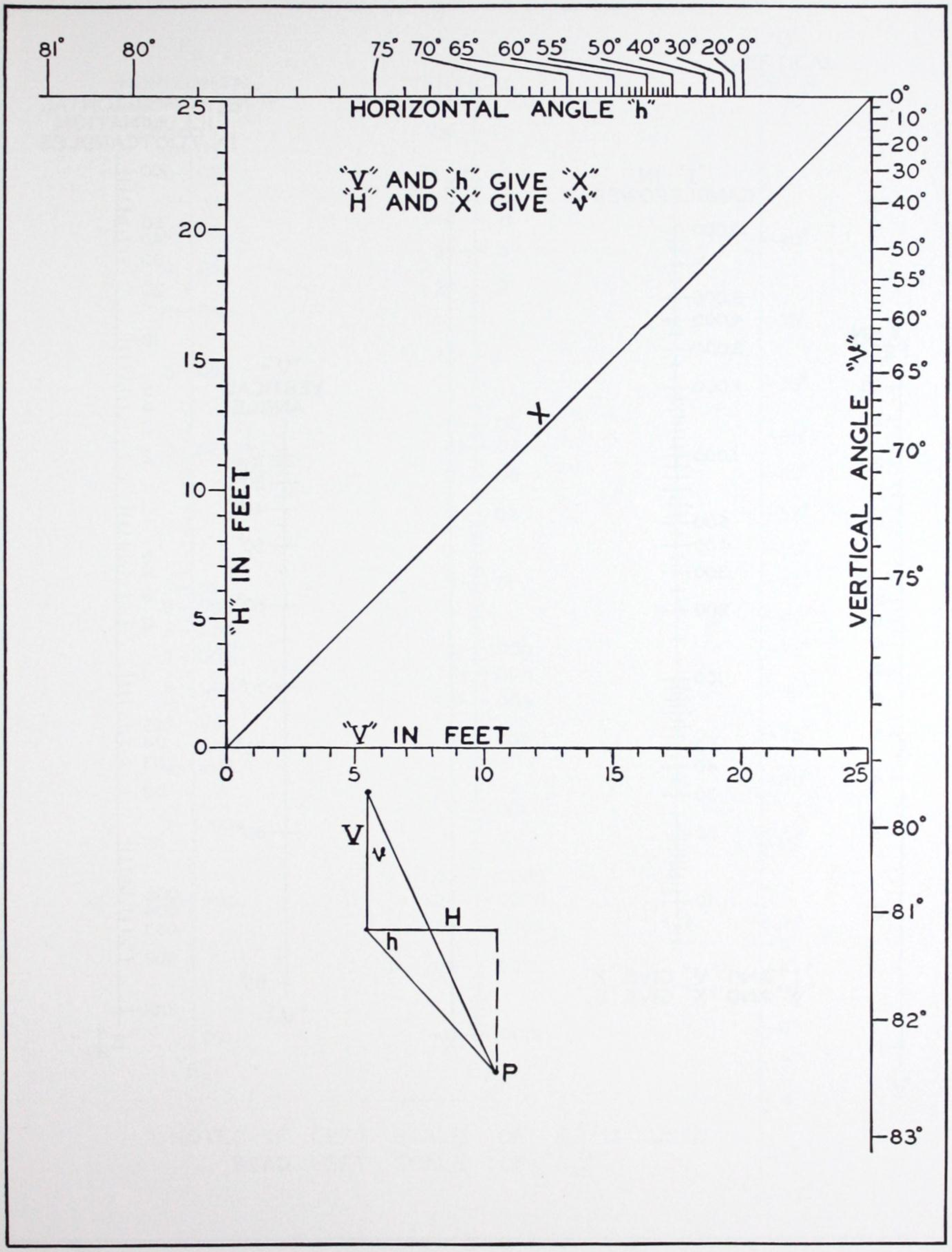


CHART II Vertical Angle

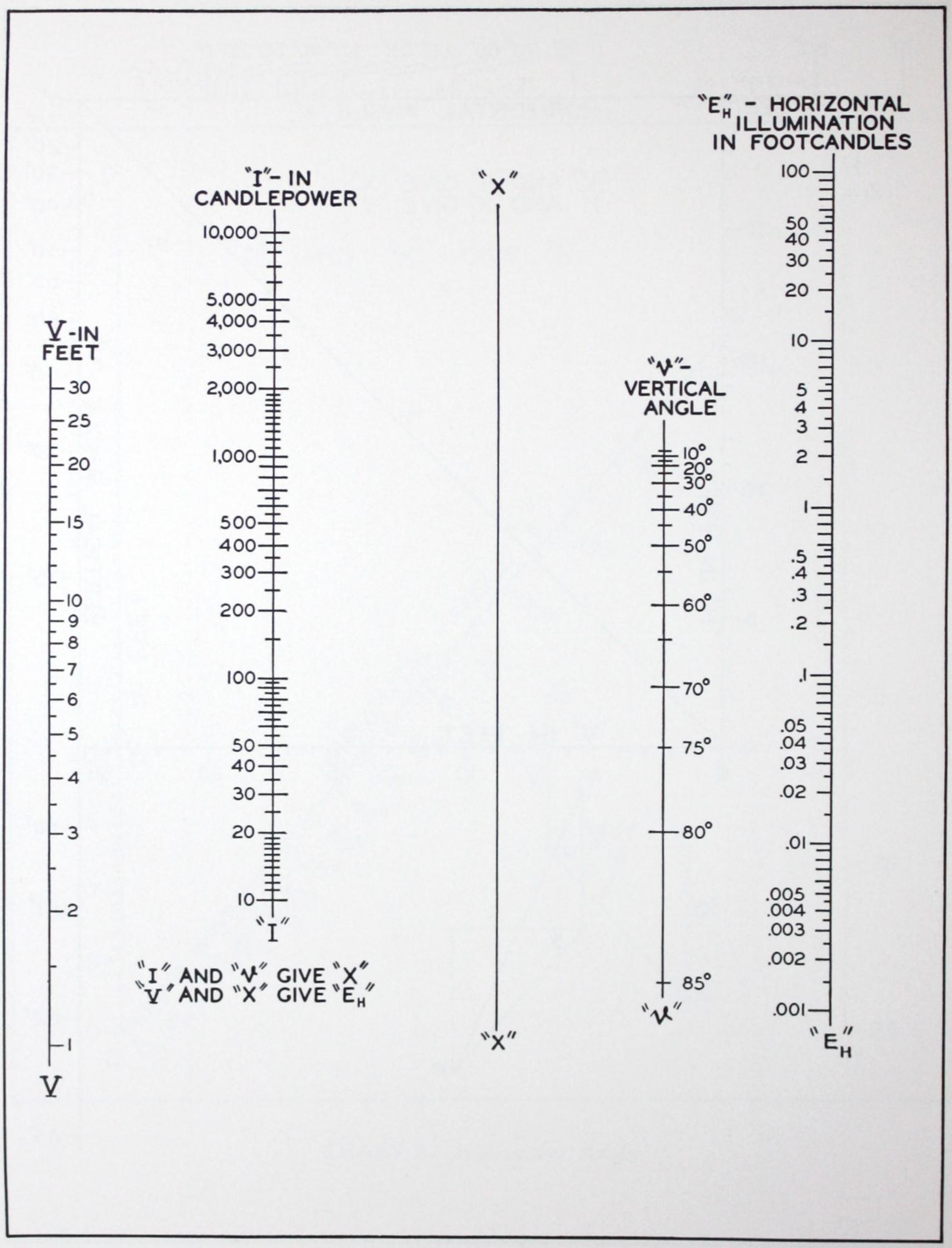


CHART III Horizontal Illumination

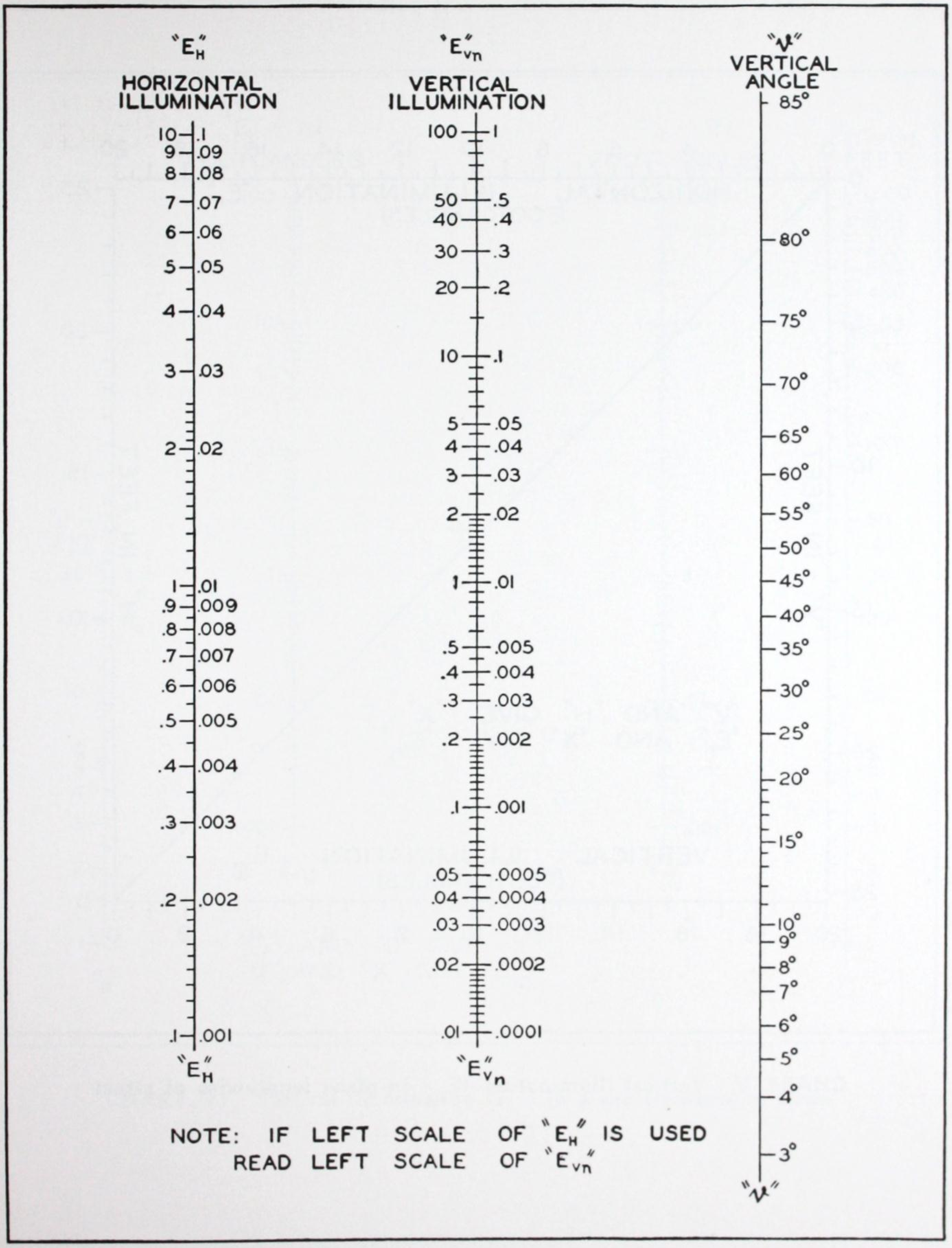


CHART IV Vertical Illumination (E_{v_n}) in plane normal to line L

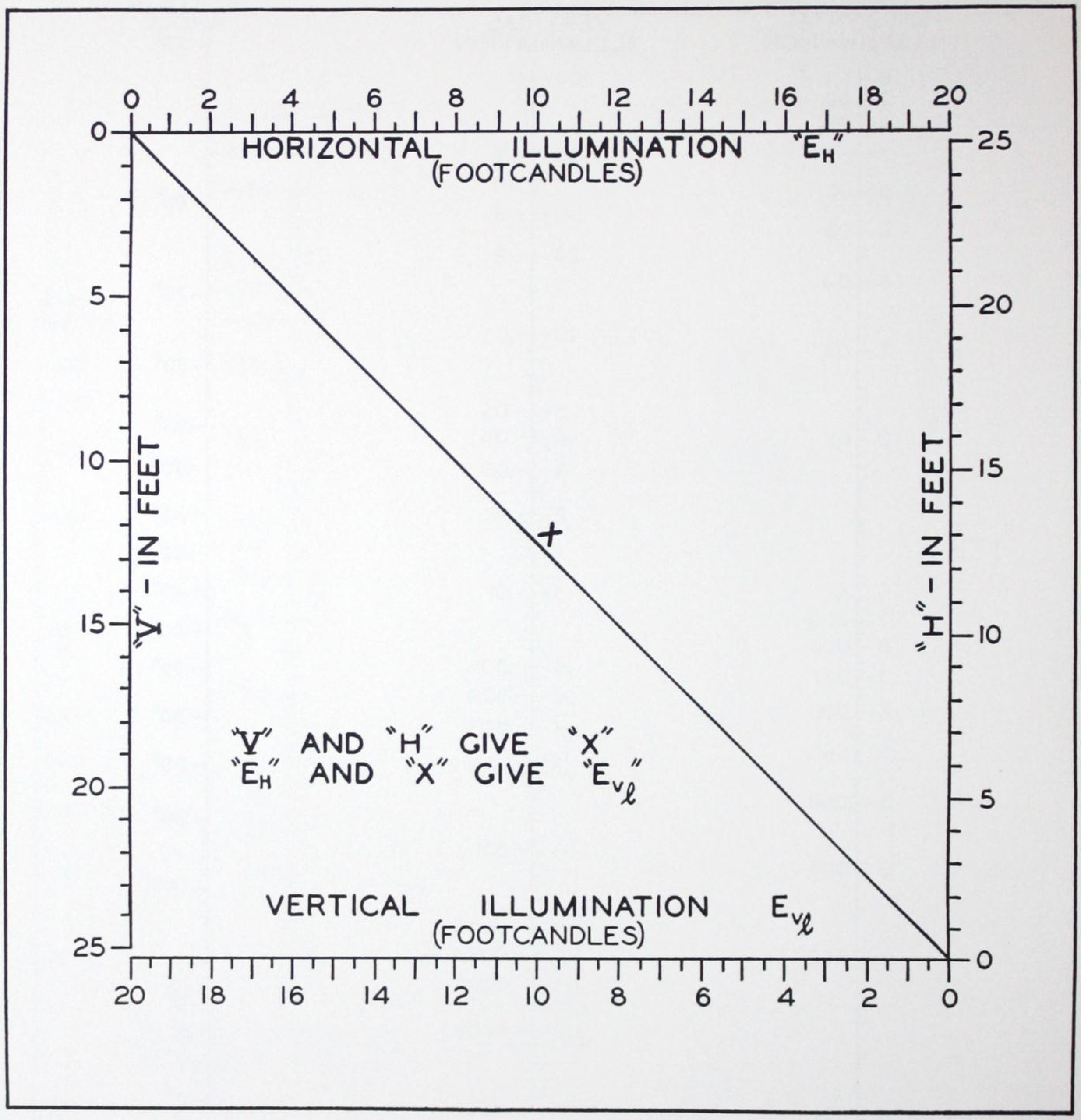


CHART V Vertical Illumination (E_{v_l}) in plane lengthwise of street

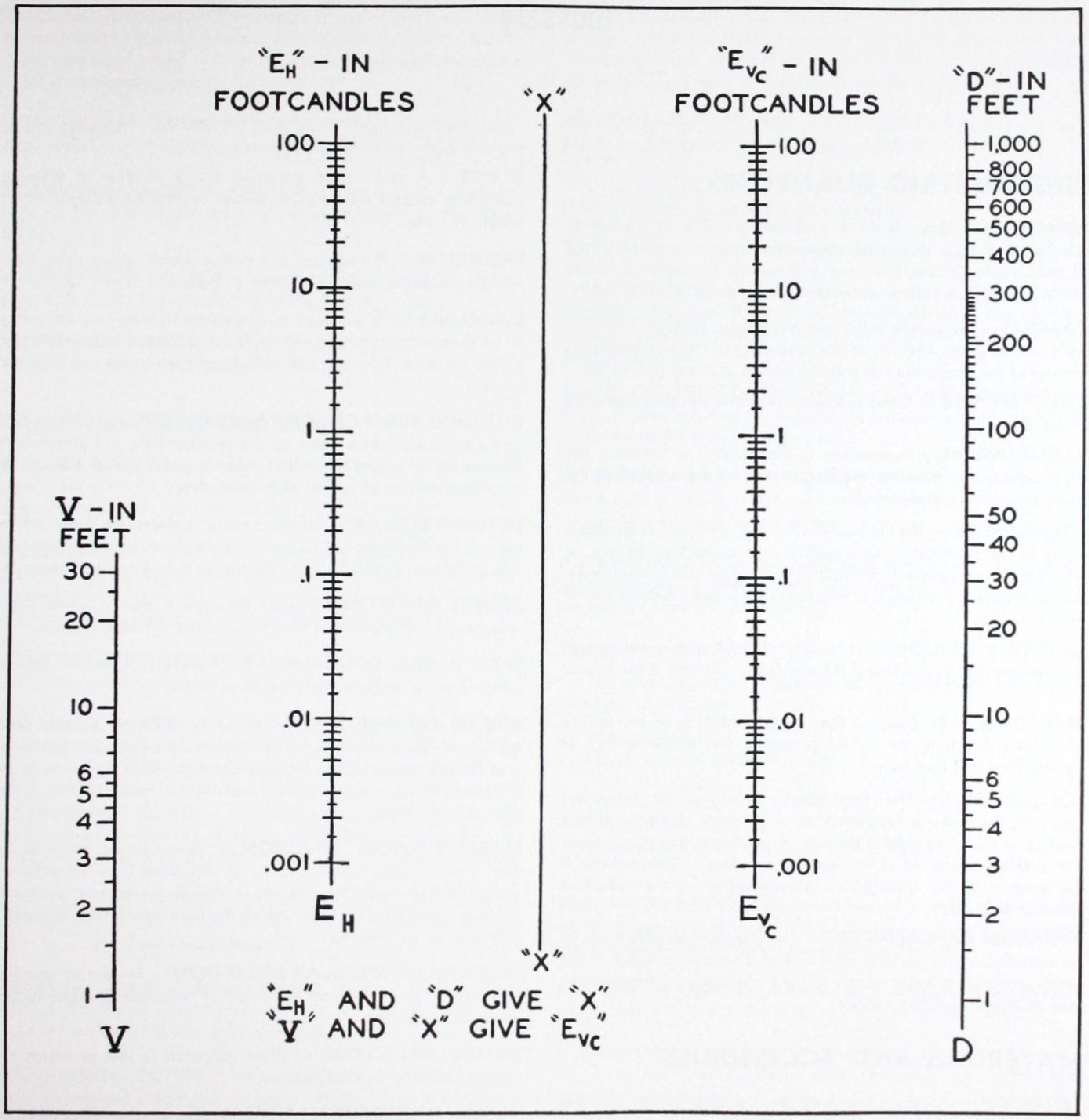


CHART VI Vertical Illumination (E_{v_c}) in plane crosswise of street

Part IX

Glossary *

PHOTOMETRIC QUANTITIES

LUMEN — The lumen is the unit of luminous flux. It is equal to the flux through a unit solid angle from a uniform point source of one candle, or the flux on a unit surface all points of which are at unit distance from a uniform point source of one candle.

CANDLE — The candle is the unit of luminous intensity. It is defined as 1/60 of the intensity of one square centimeter of a blackbody radiator at the temperature of solidification of platinum (2,046°K).

CANDLEPOWER — Candlepower is luminous intensity expressed in candles.

ILLUMINATION — Illumination is the density of luminous flux on a surface; it is equal to the flux divided by the area when the latter is uniformly illuminated.

FOOTCANDLE — The footcandle is the unit of illumination, equal to the illumination on a surface one square foot in area on which there is a uniformly distributed flux of one lumen, or illumination on a surface a distance of one foot from a uniform point source of one candle.

QUANTITY OF LIGHT — Quantity of light is the product of the luminous flux by the time it is maintained. The unit is the lumen-hour.

BRIGHTNESS — Brightness is the luminous intensity of any surface in a given direction per unit of projected area of the surface as viewed from that direction.

FOOTLAMBERT — The footlambert is a unit of brightness equal to the uniform brightness of a perfectly diffusing surface emitting or reflecting light at the rate of one lumen per square foot. The average brightness of any reflecting surface in footlamberts is the product of the illumination in footcandles by the reflection factor of the surface.

APPARENT CANDLEPOWER — The apparent candlepower of an extended source of light measured at a specific distance is the candlepower of a point source of light which would produce the same illumination at that distance.

MATERIALS AND ACCESSORIES

REFLECTOR — A reflector is a device, the chief use of which is to redirect the light of a lamp by reflection in a desired direction or directions.

REFRACTOR — A refractor is a device, usually of prismatic glass which redirects the light of a lamp in desired directions principally by refraction.

SHADE — A shade is a device, the chief use of which is to diminish or intercept the light from the lamp in certain directions where such light is not desirable. Frequently the functions of a shade and a reflector are combined in the same unit.

GLOBE — A globe is an enclosing device of clear or diffusing material to protect the lamp, to diffuse or redirect its light, or to modify its color.

PROJECTOR — A projector is a device which concentrates luminous flux within a small angle about a single axis.

LUMINAIRE — A luminaire is a complete lighting unit consisting of a light source, together with its direct appurtenances, such as the globe, reflector, housing, and such support as is integral with the housing.

DIFFUSING SURFACES AND MEDIA — Diffusing surfaces and media are those which break up the incident light and distribute it more or less in accordance with Lambert's cosine law of emission**, as for example, rough plaster and white glass.

DIFFUSE-SPECULAR — Diffuse-specular surfaces are those which are essentially diffuse but contain an outer layer of glazed material which reflects specularly. Porcelain-enamel is a common example.

PERFECT DIFFUSION — Perfect diffusion is that in which light is scattered uniformly in all directions by the diffusing medium.

WIDE ANGLE DIFFUSION — Wide-angle diffusion is that in which light is scattered over a wide angle.

SPREAD OR DIFFUSING — Spread or diffusing surfaces (and media) are those which break up the incident light and distribute it as though the surface were incandescent, uniformly bright in all directions or approximately so. Examples are rough plaster, white glass, white plastic.

NARROW-ANGLE DIFFUSION — Narrow-angle diffusion is that in which light is scattered in all directions from the diffusing medium but in which the intensity is notably greater over a narrow angle in the general direction which the light would take by regular reflection or transmission.

REGULAR OR SPECULAR REFLECTION — Regular or specular reflection is that in which the angle of reflection is equal to the angle of incidence.

DIFFUSE REFLECTION — Diffuse reflection is that in which the light is reflected in all directions.

REGULAR REFLECTION FACTOR — The regular reflection factor is the ratio of the regularly reflected light to the incident light.

DIFFUSE REFLECTION FACTOR — The diffuse reflection factor is the ratio of the diffusely reflected light to the incident light.

REFLECTION FACTOR OR REFLECTANCE — The reflection factor or reflectance is the ratio of the light reflected to the incident light.

* Most of the definitions are from "Nomenclature and Standards," published by Illuminating Engineering Society.

** Theoretically perfect diffusion follows Lambert's cosine law of emission: "The intensity of light (cp) in a certain direction radiated or reflected by a perfectly diffusing plane surface varies as the cosine of the angle between the emitted ray and a normal to the surface." The diffuse plane will be equally bright at all angles, since the projected area at any angle also varies with the cosine of the angle.

DIFFUSE TRANSMISSION — Diffuse transmission is that in which the transmitted light is emitted in all directions from the transmitting body.

REGULAR TRANSMISSION—Regular transmission is that in which the transmitted light is not diffused. In such transmission the direction of the transmitted pencil of light has a definite geometrical relation to the corresponding incident pencil of light.

REGULAR TRANSMISSION FACTOR — The regular transmission factor is the ratio of regularly transmitted light to the incident light.

DIFFUSE TRANSMISSION FACTOR — The diffuse transmission factor is the ratio of the diffusely transmitted light to the diffuse incident light.

TRANSMISSION FACTOR — The transmission factor of a body is the ratio of the light transmitted to the incident light.

ABSORPTION FACTOR — The absorption factor is the ratio of the light absorbed to the incident light.

ILLUMINATING GLASSES

WHITE GLASS —White glass is highly diffusing glass having a nearly white, milky, or gray appearance. The diffusing properties are an inherent, internal characteristic of the glass.

CASED GLASS — Cased glass is glass composed of two or more layers of different glasses, usually a clear, transparent layer to which is added a layer of white, or colored glass. The glass is sometimes referred to as flashed, multi-layer, or polycased glass.

HOMOGENEOUS GLASS — Homogeneous glass is glass of essentially uniform composition throughout its structure.

ENAMELED GLASS — Enameled glass is glass which has had applied to its surface a coating of enamel. The enamel may be white or colored and may have various degrees of diffusion.

MAT-SURFACE GLASS — Mat-surface glass is glass whose surface has been altered by etching, sand-blasting, grinding, etc., to increase the diffusion. Either one or both surfaces may be so treated.

CONFIGURATED GLASS — Configurated glass is glass having a patterned or irregular surface, usually applied during fabrication. Such glasses are somewhat diffusing.

PRISMATIC GLASS — Prismatic glass is clear glass into whose surface is fabricated a series of prisms, the function of which is to direct the incident light in desired directions.

TRANSPARENT GLASS — Transparent glass is glass having no apparent diffusing properties. Varieties of such glass are referred to as flint, crown, crystal, clear.

POLISHED PLATE GLASS — Polished plate glass is glass whose surface irregularities have been removed by grinding and polishing, so that the surfaces are approximately plane and parallel.

CHARACTERISTICS OF ILLUMINATION

COEFFICIENT OF UTILIZATION — The Coefficient of Utilization of an illumination system is the total flux on the working plane divided by the total flux from the lamps illuminating it. The plane of reference is usually assumed to be 30 inches above the floor.

PHOTOMETRIC STANDARDS AND TESTS

PRIMARY LUMINOUS STANDARD — A primary luminous standard is one by which the unit of light is established and from which the values of other standards are derived. A satisfactory primary standard must be reproducible from specifications.

SECONDARY STANDARD — A secondary standard is one calibrated by comparison with a primary standard.

WORKING STANDARD—A working standard is any standardized luminous source for daily use in photometry.

TEST LAMP — A test lamp, in a photometer, is a lamp to be tested.

CHARACTERISTIC CURVE — A characteristic curve is a curve expressing a relation between two variable properties of a luminous source, as candlepower and volts, candlepower and rate of fuel consumption, etc.

CURVE OF LIGHT DISTRIBUTION — A curve of light distribution is a curve showing the variation of luminous intensity of a lamp or luminaire with angle of emission.

SYMMETRICAL LIGHT DISTRIBUTION — A symmetrical light distribution is one in which the curves of vertical distribution are substantially the same for all planes.

ASYMMETRICAL LIGHT DISTRIBUTION — An asymmetrical light distribution is one in which the curves of vertical distribution are not the same for all planes.

ABBREVIATIONS

The following abbreviations have been adopted by the American Standards Association:

Candlepower	cp
Mean horizontal candlepower	mhcp
Spherical candlepower	scp
Lumens per watt	lpw
Footcandle(s)	fc
Footlambert(s)	fL

BRIGHTNESS RATIO — Brightness ratio is the ratio of the brightnesses of any two surfaces. When the two surfaces are adjacent, the brightness ratio is called the brightness contrast.

COLORS OF OBJECTS — The color of an object is the capacity of the object to modify the color of the light incident upon it.

COLORANTS — Substances which are used to produce the colors of objects are called colorants (dyes, pigments, inks, paints, and decorative coatings).

DOMINANT WAVELENGTH — The wavelength of homogeneous light, which when combined with white light in suitable proportions, matches a color, is the dominant wavelength of the color.

COMPLEMENTARY WAVELENGTH — The wavelength of homogeneous light, which when combined with a sample color in suitable proportions matches the adopted white light, is the complementary wavelength of the sample.

PURITY — The relative brightnesses of the spectrum and white components in a color mixture.

CHROMATICITY — Chromaticity is the expression of dominant wavelength and purity. For purples, which are mixtures of colors, chromaticity is expressed in terms of wavelength and purity of the complementary color.

ILLUMINANTS

LAMP — The term lamp is the generic term for an artifical source of light.

FILAMENT LAMP — A filament lamp is a light source consisting of a glass bulb containing a filament electrically maintained at incandescence.

ELECTRIC DISCHARGE LAMP — An electric discharge lamp is a lamp in which light is produced by the passage of electricity through a metallic vapor or gas enclosed in a tube or bulb.

FLUORESCENT LAMP — A fluorescent lamp is an electric discharge lamp in which the radiant energy from the electric discharge is transferred by suitable materials (phosphors) into wavelengths giving higher luminosity.

EFFICIENCY OF A LIGHT SOURCE — The efficiency of a light source is the ratio of the total luminous flux to the total power input. In an electric lamp it is expressed in lumens per watt.

COLOR TEMPERATURE — The color temperature of a source of light is the temperature at which a blackbody must be operated to give a color matching that of the source in question.

MEAN HORIZONTAL CANDLEPOWER — The mean horizontal candlepower of a lamp is the average candlepower in the horizontal plane passing through the luminous center of the lamp. It is assumed that the lamp or other light source is mounted in the usual manner, as in the case of a filament lamp, with its axis of symmetry vertical.

SPHERICAL CANDLEPOWER — The (mean) spherical candlepower of a lamp is the average candlepower of the lamp in all directions in space. It is equal to the total luminous flux of the lamp in lumens divided by 4π.

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GENERAL ELECTRIC

GENERAL ELECTRIC LARGE LAMP SALES AND SERVICE DISTRICT OFFICES

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